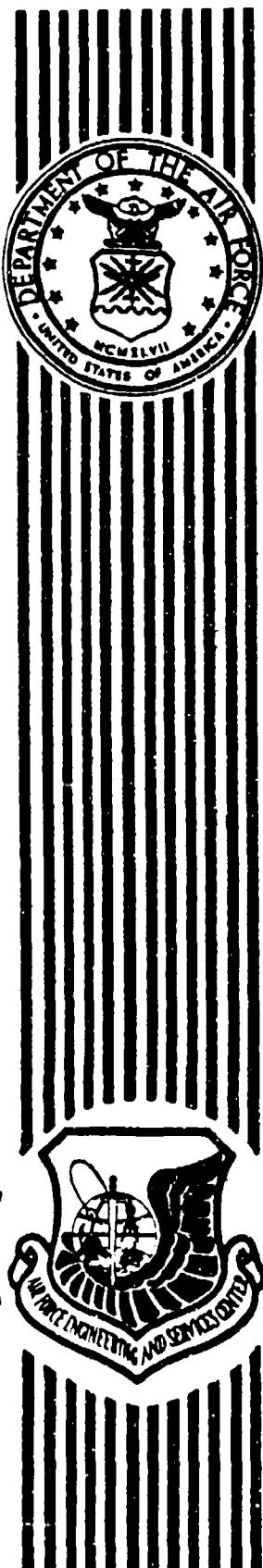


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SIMULATION OF THE THERMAL RE-
SPONSE OF EXTERNALLY COOLED ORD-
NANCE ENGULFED IN LARGE AVIATION
FUEL FIRES

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LARGE AVIATION FUEL FIRES

EXECUTIVE SUMMARY

Evaluation and quantification of the response time of various munitions to accidental fire impingement is an integral part of the DOD's ordnance thermal protection program. The thermal protection program involves interaction of numerous thermodynamic and heat transfer disciplines. This report presents exclusively the efforts on numerical and experimental simulations of the effects on ordnance cookoff time when external cooling is applied.

To assess effects of the external cooling on fire-exposed ordnance cookoff time, a validated heat transfer computer model was adopted and modified to include principles describing the external cooling effects. The new model predicts the change in ordnance cookoff time as a function of coolant application rate. Calculations demonstrate that external cooling can delay the cookoff time.

The thermal interaction between the incident flame and ordnance, as well as the effects of coolant on cookoff time, were simulated experimentally. Specially designed calorimeters were instrumented and placed in a pool fire to measure the transient heat flux and to quantify the effects of various coolants. Effect of an intumescence coating used on various ordnance was evaluated experimentally and compared with the response of the thermally unprotected ordnance. The limited experimental data, although inconclusive, suggest that thermally unprotected ordnance can achieve longer cookoff times than coated ordnance, when external cooling is applied.

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PREFACE

This final report was prepared by the New Mexico Engineering Research Institute (NMERI), University of New Mexico, Campus Box 25, Albuquerque, New Mexico 87131, under Contract F29601-84-C-0080 (Subtask 3.10) for the Air Force Engineering and Services Center (AFESC/RDCF), Tyndall Air Force Base Florida 32403, and the Naval Air Systems Command (NAVAIR), Washington, DC 20361.

This report summarizes work done between 14 January 1985 and 30 October 1986. HQ AFESC/RDCF Program Manager was Joseph L. Walker, and NAVAIR Project Officer was Phyllis Campbell.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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LIST OF SYMBOLS

T :	Temperature	K
T_w :	Coolant temperature	K
T_f :	Flame temperature	K
T_s :	Surface temperature	K
ϵ :	Emissivity coefficient	
σ :	Stefan Boltzman constant	cal/s m^2 K
q_f :	Incident heat flux from fire	cal/s m^2
q :	Internal energy generation	cal/s
U_{oa} :	Overall heat transfer coefficient	cal/s K
Q :	Heat of reaction	cal/g
C_p :	Specific heat at constant pressure	cal/g K
Z :	Collision number	liter/s
K :	Thermal conductivity	cal/cm 2 s K
E :	Activation energy	cal/mole
ρ :	Density	g/cm 3
R :	Universal gas constant	cal/mole K
t :	Time	second
ℓ :	Current layer	
n :	Total number of layers	
m :	Number of components of the explosive	
i :	Represents the calculation node, spatial coordinate	
j :	Represents the current time, time step	
ΔF :	Fourier modulus	
Δr :	Elemental radial width	
h :	Convective heat transfer coefficient	cal/s K
R :	Radius	cm

SECTION I
INTRODUCTION

A. OBJECTIVE

This project was conducted to calculate the response time for fire-exposed ordnance and determine how long ordnance cookoff can be delayed by application of external cooling. Different coolant types and application techniques were tested to develop pragmatic criteria for response times and cooling procedures to be used for ordnance exposed to fire.

B. BACKGROUND

The US armed forces have had a number of incidents in which ordnance exposed to fire has cooked off, causing major loss of life and property. Incidents on the USS Forrestal, USS Enterprise, and the USS Nimitz all resulted in losses of life and materiel (References 1, 2, and 3). The USAF has also had such incidents; for example, a maintenance accident at Mountain Home AFB resulted in the burning of an F-111 loaded with Mark 82 bombs. In this incident the firefighters retreated and all of the bombs cooked off, resulting in significant materiel losses.

In the event of a postcrash fire, it is likely that ordnance will be exposed to high heat fluxes. Ordnance reactions (propulsion or detonation depending on the nature of the weapon) to a fire environment can range from mild burning to violent explosion. The extent of the reaction is determined by the intensity and duration of heating, and the thermal protection of the ordnance. The ordnance may have a cookoff reaction after removal of the heat source (usually by fire extinguishment) because of self-heating from internal exothermal reactions. Firefighting efforts and the associated hazards are complicated when fire-exposed ordnance are present. Criteria are not available to accurately define the cooling/handling requirements and safe response procedures to be used for ordnance exposed to fire.

C. SCOPE

The scope of this project was to investigate and evaluate all existing ordnance response models and to modify a viable candidate to include the effects of external cooling. The modified model was to be capable of predicting the cooling required to prevent a runaway reaction and to assess the cookoff time extension resulting from external cooling. Small-scale calorimeter tests were conducted to obtain essential parameters needed to calculate cookoff time extensions which can be achieved by application of external cooling. To evaluate the effects of intumescent thermal protection on cookoff time extension, coated calorimeters were tested and the data were compared with the response data from uncoated calorimeters.

D. APPROACH

This report documents numerical modeling conducted as one component of a long range effort to reduce losses from ordnance cookoff. Numerical models which predict the transient response of ordnance exposed to heat fluxes have been developed in the past. One of these models has been updated to include external cooling and its effect on ordnance response. Testing of subscale models has been used to measure the effectiveness of various coolants, with their heat transfer rates used as input to the computer model. The change in cookoff time as a function of coolant application rate is then predicted.

SECTION II

MATHEMATICAL MODELING

A. INTRODUCTION

The derivation of heat transfer equations describing the thermal loading of an ordnance is based on the physical model shown in Figure 1. In this figure various components of a typical ordnance (a Mark 82 general purpose bomb) are shown in a sector cross section. Each layer is characterized by its thickness and thermal properties; perfect thermal contact between each of the layers is assumed. Internal energy generation due to chemical reaction is allowed in any layer. The energy generation is modeled by the use of first-order Arrhenius kinetics. The ordnance is assumed to be immersed in a large aviation fuel fire, which is characterized by a flame temperature. The

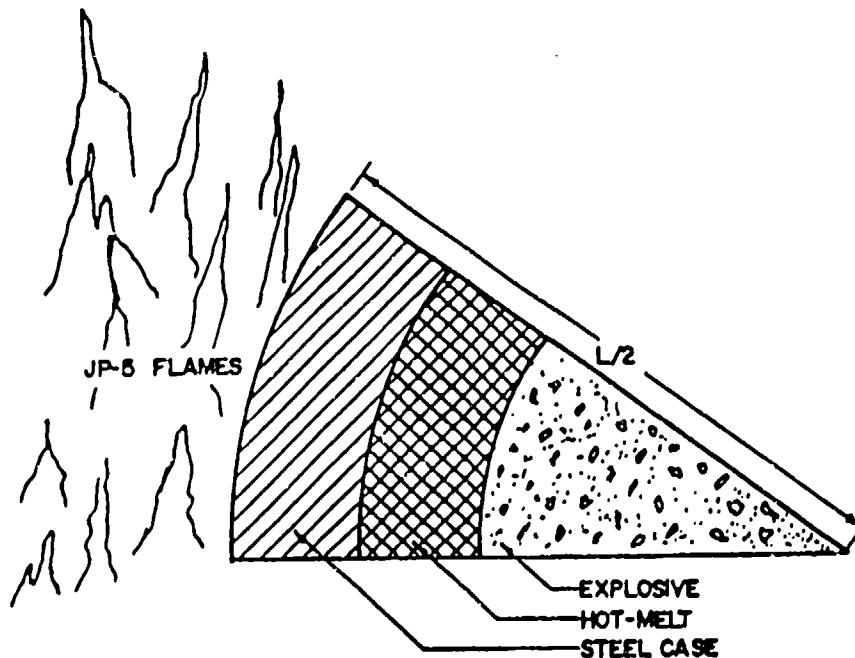


Figure 1. Sector of Cylindrical Cross Section of a General-Purpose Bomb, Mark 82 (extracted from Reference 4).

heat flux input from the fire to the ordnance is modeled with radiative and convective components. Ordnance cookoff is defined as the point where the explosive begins a thermally induced, exothermic, runaway decomposition. This process is modeled by use of the first-order Arrhenius kinetics.

B. GOVERNING EQUATIONS

The governing equations describing the overall heat transfer processes in a fire-exposed ordnance must include:

1. Equations describing the incident external heat flux.
2. Equations describing the heat transfer through various internal layers.

C. EXTERNAL HEATING

The total incident heat flux on the exterior boundary of the ordnance, q_f , is equal to the sum of radiative and convective heat flux.

$$q_f = \epsilon \sigma (T_f^4 - T_s^4) + h (T_f - T_s)$$

with the terms defined as follows:

- T_f : flame temperature
 T_s : surface temperature
 ϵ : emissivity factor
 σ : Stefan Boltzman constant
 h : convective heat transfer coefficient

The incident flame temperature history used in the program was taken from JP-5 fire data presented by Russell and Canfield (Reference 4). The emissivity factor of the fire is assumed to be 0.99. The convective heat transfer coefficient is taken from Boyer and Russell (Reference 5). During cooling, the surface boundary condition is modeled using

$$q = U_{oa} (T_w - T_s)$$

where U_{oa} is the overall heat transfer coefficient and T_w is the coolant temperature. The values for U_{oa} were obtained from experimental data provided by the subscale calorimeter tests.

D. INTERNAL HEATING

Heat is transferred through various layers of munitions by conduction. The governing internal heat transfer equation is the algebraic sum of conduction and internal energy of the materials at each layer. The internal heat transfer equation in cylindrical coordinates becomes:

$$\rho_l C_{pl} \frac{\partial T_l}{\partial t} = k_l \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T_l}{\partial r} \right) \right] + \dot{q}_l \quad l = 1, \dots, n \quad (1)$$

The terms in the energy equation are defined as follows:

l : layer index

n : total number of layers

ρ : density (g/cm^3)

C_p : specific heat (cal/g K)

T : temperature (K)

t : time (seconds)

k : thermal conductivity ($\text{cal/cm}^2 \text{s K}$)

r : radius (centimeters)

\dot{q} : rate of internal energy generation (cal/s)

The rate of internal energy generation (\dot{q}) is expressed as a first-order Arrhenius reaction:

$$\dot{q} = \rho_l \sum_{p=1}^m Q_p Z_p \exp \left(-E_p / R T_i \right) \quad (2)$$

where

m: number of components of the explosive
 i: represents the calculation node
 Q: heat of reaction (cal/g)
 Z: collision number (liters/s)
 E: activation energy (cal/mole)
 R: universal gas constant (cal/mole K)

E. BOUNDARY CONDITION AND ASSUMPTIONS

The above governing equations are solved according to the following boundary conditions:

The outer boundary condition is

$$-k_l \frac{\partial T_l}{\partial r} = \epsilon \sigma (T_f^4 - T_s^4) + h (T_f - T_s) \quad (3)$$

Similarly, the boundary condition for the period of cooling becomes

$$-k_l \frac{\partial T_l}{\partial r} = U_{oa} (T_w - T_s) \quad (4)$$

The boundary condition at each interface assumes that the heat flux across the boundary is equal on both sides of the interface and the temperatures are the same. This is expressed as:

$$k_l \frac{\partial T_l}{\partial r} = k_{l+1} \frac{\partial T_{l+1}}{\partial r} \quad (5)$$

and

$$T_l = T_{l+1} \quad (6)$$

Furthermore, it is assumed that the variation of the temperature at the center of the ordnance is finite, therefore

$$\frac{\partial T_\ell}{\partial r} = 0, \text{ at } r=0 \quad (7)$$

and the ordnance is initially at the ambient temperature

$$T = T_{\text{amb}} \quad (8)$$

F. FINITE DIFFERENCING METHOD

The governing heat transfer principles and the boundary conditions described in Equations (1) through (8) are solved numerically using a finite differencing scheme. The algorithm used to obtain an approximate numerical solution is based on an explicit central differencing method (Reference 6). The spatial location of each finite element is based on the cylindrical distribution of Δr as shown in Figure 2.

Expressed in the finite-difference form, the partial differential Equation (1) describing the energy transfer at each layer becomes

$$T_i^{j+1} - T_i^j + \frac{[\Delta F_i^j + 0.25(\Delta F_{i-1}^j - \Delta F_{i+1}^j)][r_i + 0.5 \Delta r_1](T_{i-1}^j - T_i^j)}{r_i} + \frac{[\Delta F_i^j + 0.25(\Delta F_{i-1}^j - \Delta F_{i+1}^j)][r_i - 0.5 \Delta r_1](T_i^j - T_{i+1}^j)}{r_i} + \frac{\Delta F_i^j (\Delta r)^2}{(k_\ell)_i^j} \dot{q} \quad (9)$$

where i represents the current node and j represents the current time. The internal energy term is expressed as

$$\dot{q} = \rho_\ell \sum_{n=1}^m Q_{\ell,n} Z_{\ell,n} \exp(-E_n / R T_i^j) \quad (10)$$

where n represents the current reactive component, m represents the total number of reactants, and ℓ represents the current layer. The Fourier modulus, ΔF , is defined as

$$\Delta F_i^j = \frac{k_i^j \Delta t}{\rho_\ell C p_\ell (\Delta r)^2} \quad (11)$$

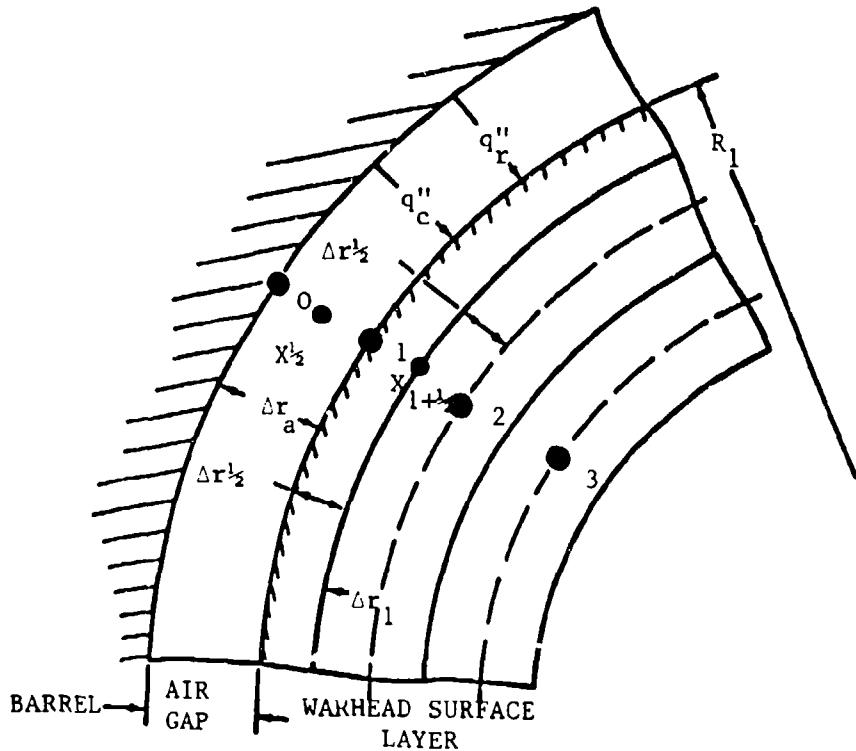


Figure 2. Elemental Surface Layer Analog.

The surface boundary condition, Equation (3), in finite difference form is

$$T_i^{j+1} = T_i^j + \Delta F_1^j \frac{(\Delta r_1)^2}{k_i^j} \dot{q} + 2 \frac{\Delta F_1^j (r_t) (\Delta r_1)}{k_1^j (r_t - \Delta r_1/4)} [h (T_f - T_1^j) + \epsilon \sigma (T_f^4 - (T_1^j)^4)] - \Delta F_1^j \frac{(r_t - \Delta r_1/2)}{(r_t - \Delta r_1/4)} [T_1^j - T_2^j] \quad (12)$$

The surface boundary condition during cooling is expressed as

$$T_i^{j+1} = T_i^j + \Delta F_1^j \frac{(\Delta r_1)^2}{k_i^j} \dot{q} + 2 \frac{\Delta F_1^j (r_t) (\Delta r_1)}{k_1^j (r_t - \Delta r_1/4)} [U_{oa} (T_w - T_1^j)] - \Delta F_1^j \frac{(r_t - \Delta r_1/2)}{(r_t - \Delta r_1/4)} [T_1^j - T_2^j] \quad (13)$$

The interface boundary condition between layers is expressed as

$$T_1^{j+1} = T_1^j + \frac{2\theta_1 \Delta x_1}{K_1 (1 - \frac{\Delta x_1}{4})} \cdot [x_1 \sigma F_{1-0} (T_0^j)^4 - (T_1^j)^4] + \frac{2\theta_1 \Delta x_1}{K_1 (1 - \frac{\Delta x_1}{4})} \cdot [K_1 (x_1 - \frac{\Delta x_1}{2}) \cdot (\frac{T_2^j - T_1^j}{\Delta x_1}) + \frac{2\theta_1 \Delta x_1}{K_1 (1 - \frac{\Delta x_1}{4})} \cdot [K_a (x_1 + \frac{\Delta x_a}{2}) \cdot (\frac{T_0^j - T_1^j}{\Delta x_1})] + \frac{2\theta_1 \Delta x_1}{K_1 (1 - \frac{\Delta x_1}{4})} \cdot [(x_1 + \frac{\Delta x_1}{4}) (\frac{\Delta x_1}{2}) \dot{q} \dots] \quad (14)$$

where:

$$\theta_1 = \frac{K_1 \Delta t}{\rho_1 c_1 (\Delta x_1)^2}$$

$$x_{1+1/2} = x_1 + \frac{\Delta x_1}{2}$$

$$x_{1/2} = x_1 + \frac{\Delta x_a}{2}$$

$$F_{1-0} = \frac{1}{\left[\frac{1}{\epsilon_1} + \left(-\frac{A_1}{A_0} \right) \left(\frac{1}{\epsilon_0} - 1 \right) \right]}$$

The coefficient F_{1-0} is the gray-body shape factor resulting from the radiative heat transfer processes (Reference 7). The center boundary condition expressed in finite difference becomes

$$T_i^{j+1} = T_i^j + 2 \left(\frac{k_i^j \Delta t}{\rho_i C p_i (\Delta r_i)^2} \right) (T_{i-1}^j - T_i^j) + \frac{q_i^j}{\rho_i C p_i} \quad (15)$$

A FORTRAN program was written to solve the governing differencing Equations (9) through (15). Details of the computer model are discussed in the next section.

SECTION III

COMPUTER MODEL

A. INTRODUCTION

The finite difference equations used to calculate the temperature profiles through the ordnance were implemented in a computer program. A flowchart of the program is contained in Appendix A and the program listing is in Appendix B. The program is a modified version of one originally written by Russell and Canfield (Reference 4) and later modified by Boyer and Russell (Reference 5). The program is written in FORTRAN and consists of a driver program and several subroutines. Each subroutine calculates one of the three temperature types (surface, interior, or interface node), or performs other tasks required by the program. The model has been executed on a 16-bit desk-top computer. The program is interactive; it requests the user to enter the data and output file names. The input data consist of dimensions, thermal properties of each of the layers, flame, and cooling parameters, and program control parameters. The input data required by the program are listed in Appendix C.

B. COMPARISON WITH OTHER MODELING AND EXPERIMENTAL DATA

The model was tested by executing several cases to ensure that cookoff times were predicted correctly. All of the cookoff tests were conducted with ordnance engulfed in JP-5 fires. The model results were first compared to results obtained by Russell and Canfield (Reference 4) with their flat-plate ordnance model. Reference 4, Appendix B, Table 3, Case 1 was used as a baseline. Russell and Canfield predicted a cookoff time of 229.7 seconds. The current model predicts a cookoff time of 240.2 seconds.

Russell and Canfield also presented data for Mark 82 bombs with what was then the standard hot-melt thickness. The average time for reaction for the three tests (Reference 4, Appendix B, Table 5) was 196 seconds. Measured hot-melt layer thicknesses were not available for these tests, but radiographs were taken

of 10 bombs randomly selected from different production runs. The average of the hot-melt thicknesses for the 10 bombs was 0.33 cm. Using the value of 0.33 cm for the hot-melt thickness, the computed reaction time for a Mark 82 bomb using the current model is 184.5 seconds.

C. W. Morris (Reference 8) also presented cookoff data that were used for comparative purposes. Table 1 presents a summary of experimental and comparative predicted cookoff times for five different cases.

TABLE 1. COOKOFF TIMES FOR MARK 82 AND MARK 84 BOMBS
WITH AND WITHOUT FM-26 ABLATIVE COATING

Case	Ordnance	FM-26 thickness, mils	Hot-melt thickness, mils	Experimental cookoff time, s	Morris model time, s	NMERI model time, s
1	Mark 82	none	125	180	169	182
2	Mark 82	128	250	628	640	624
3	Mark 84	none	125	182	196	228
4	Mark 84	none	300	309	264	320
5	Mark 84	60	300	525	528	526

Agreement between the model and experimental results is generally good. For the remainder of this report, ordnance with the FM-26* ablative coating will be referred to as coated ordnance, and those without will be referred to as uncoated.

*FM-26 is an ablative coating manufactured by AVCO Corporation, Wilmington, Massachusetts 01887. This material is used as an insulator, for thermal protection on most nonpropelled Navy ordnance.

C. EFFECTS OF COOLING

When coolant is applied to an engulfed ordnance, extension of the cookoff time can be expected. The cookoff time extension depends on many parameters. The parameters contributing most effectively to the cookoff-time extension are the overall heat transfer coefficient, cooling initiation time, and coolant temperature.

A series of calculations was made to determine the dependency of the cookoff time on the overall heat transfer coefficient and the start of cooling time. The values chosen for the overall cooling coefficient, U_{oa} , were taken from the result of the subscale calorimeter testing reported in sections IV and V. The dependency of the cookoff time on the overall heat transfer coefficient and the start of the cooling time is shown in Figures 3, 4, and 5. Each of these figures shows a composite cookoff time prediction, based on the calculation, for an uncoated ordnance.

Figure 3 is a composite illustration of the cookoff time prediction for an uncoated Mark 82 bomb. The figure shows that, for any U_{oa} greater than $10^{-5} \text{ cal/cm}^2 \text{ s K}$, ordnance cookoff can be prevented if cooling starts at any time before about 150 seconds after fire initiation. For the same coefficient, if cooling starts 160 seconds after fire initiation, cookoff can be delayed approximately 40 seconds. If the cooling initiation is delayed another 10 seconds, i.e., until 170 seconds, the increase in cookoff time is negligible (less than 10 seconds). A similar trend is shown for the heat transfer coefficient U_{oa} of $10^{-4} \text{ cal/cm}^2 \text{ s K}$. Cookoff can be prevented if cooling starts at any time before 155 seconds after fire initiation.

Similarly, Figures 4 and 5 illustrate the cookoff time versus cooling initiation predictions for uncoated Mark 84 general-purpose bombs with different hot-melt thicknesses. Analogous to the analysis performed on Figure 3, one can estimate the cookoff time for various values of U_{oa} . The key to safe and successful cookoff prevention is to apply the coolant before the exothermic runaway decomposition of the explosive inside the ordnance begins.

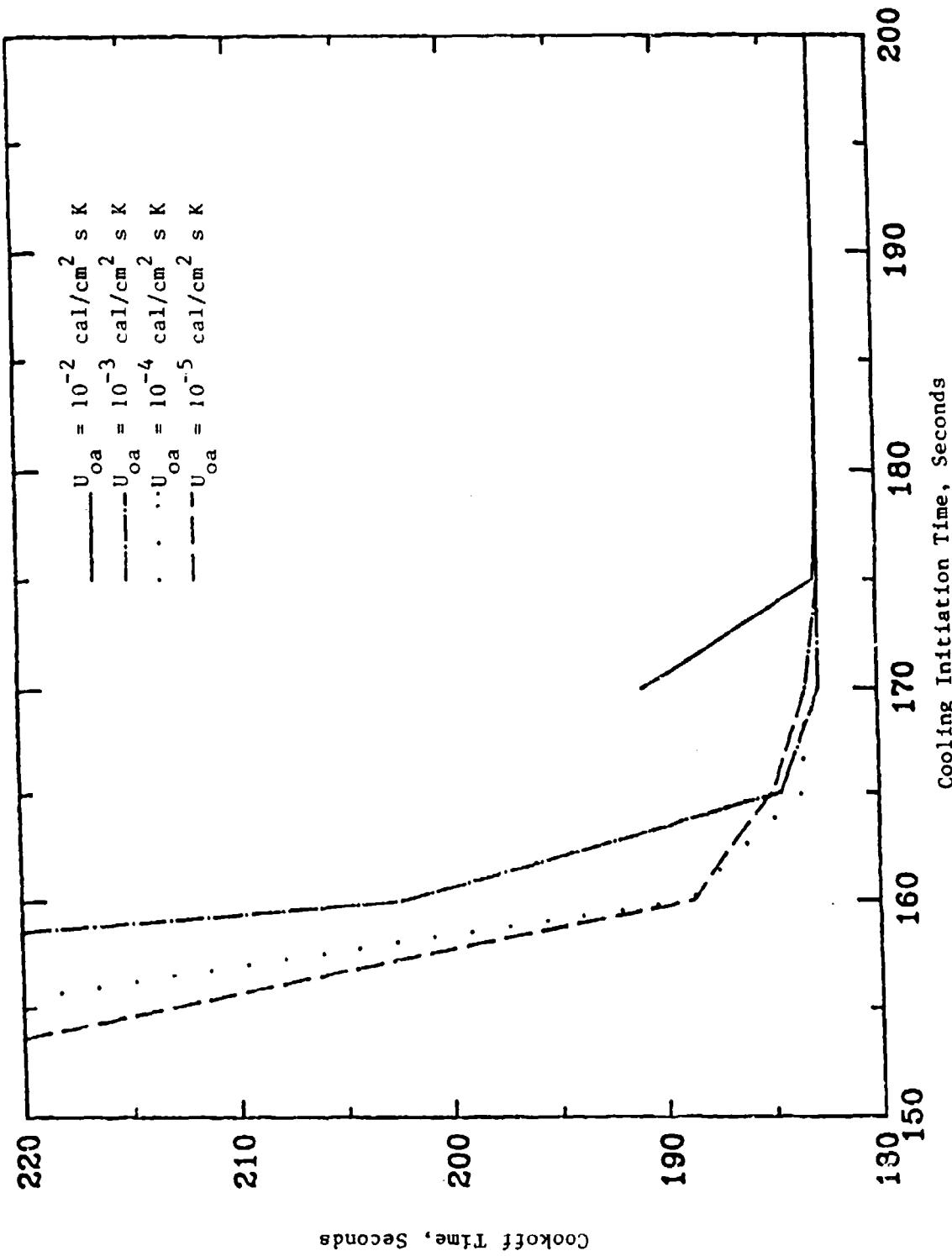


Figure 3. Cookoff Time Versus Cooling Initiation Time Profile
(Mark 82, Uncoated, Table 1, Case 1).

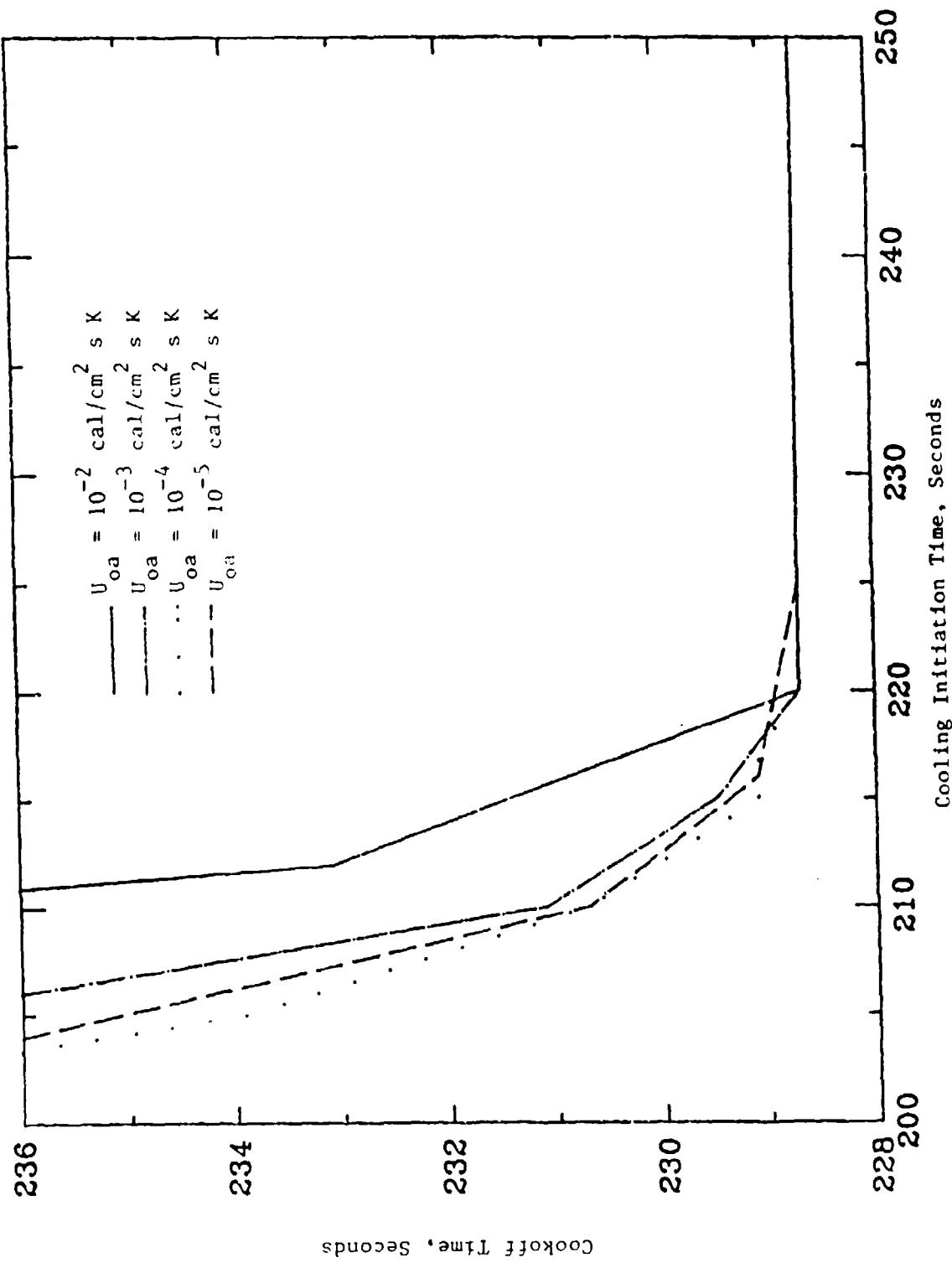


Figure 4. Cookoff Time Versus Cooling Initiation Time Profile
(Mark 84, Uncoated, Table I, Case 3).

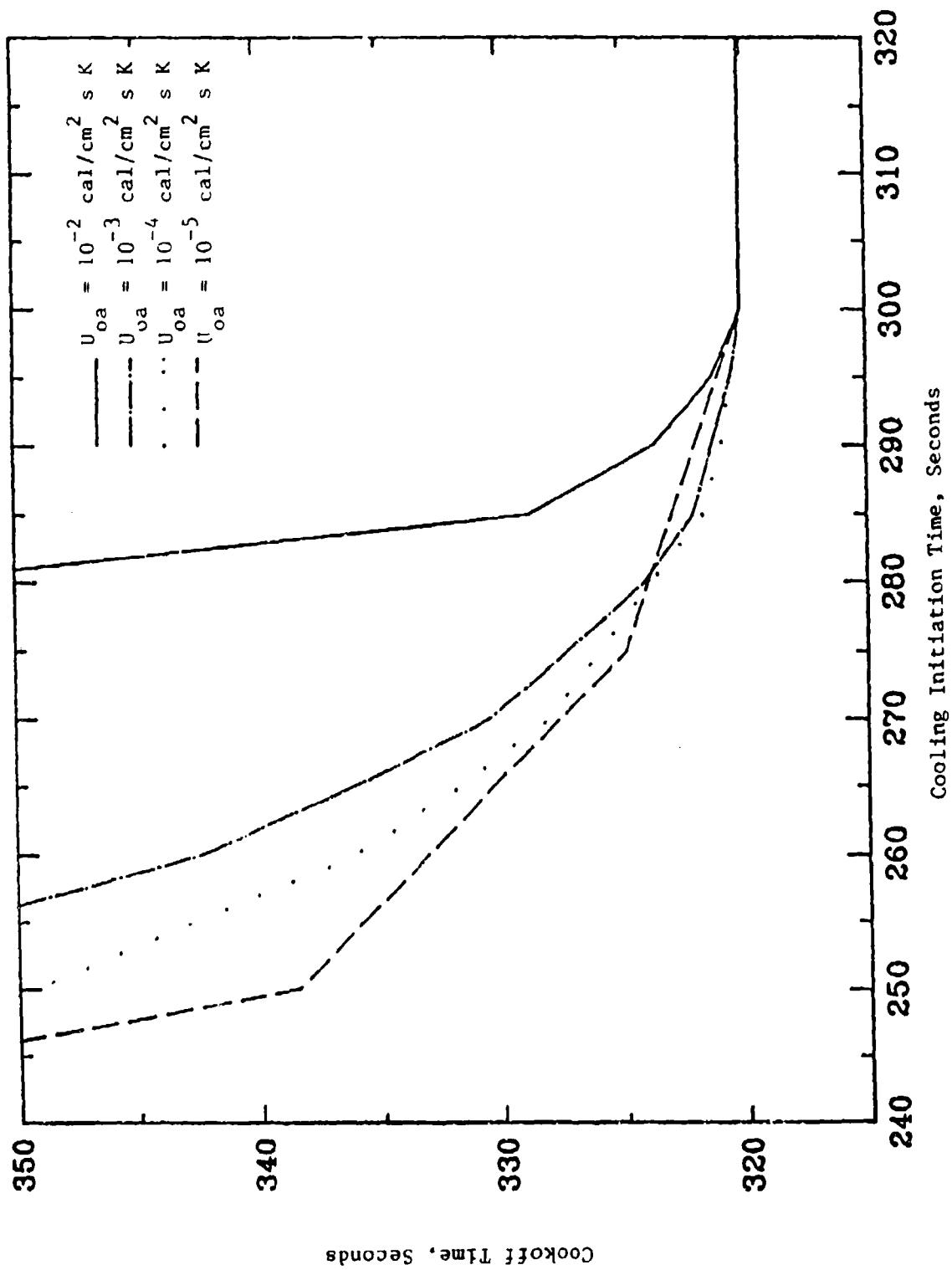


Figure 5. Cookoff Time Versus Cooling Initiation Time Profile
(Mark 84, Uncoated, Table 1, Case 4).

SECTION IV
SUBSCALE TESTING

A. INTRODUCTION

Specially designed calorimeter tests were conducted to obtain overall heat transfer coefficients essential to the cooling module of the computer model. The tests were also designed to validate the performance of the model. The calorimeters were placed in turbulent fires from a stagnant pool and cooled with various cooling agents.

Water, AFFF, Halon 2402, and liquid nitrogen were investigated as cooling agents. Water was chosen as a baseline agent because of its cooling capacity and its use in previous cooling studies. AFFF was chosen because it provides a blanket which covers and secures the fuel instead of carrying it to other areas as water does (Reference 9). AFFF is also the most likely agent to be used in a real fire situation. Studies show that AFFF does not cool as effectively as water. However, it extinguishes the fire while cooling the ordnance, and may be a better overall control agent for that reason (Reference 10). Halon 2402 was tested because of its superior ability to provide rapid knockdown, three-dimensional effectiveness, and slight cooling capacity. It was thought that the Halon 2402 would extinguish the fire rapidly while providing the initial cooling. Liquid nitrogen was chosen as a cooling agent for coated ordnance because the traditional cooling agents (water and AFFF) were unable to provide any significant cooling to coated ordnance during earlier test programs.

B. PREVIOUS WORK

Experimental and theoretical studies of the response (cookoff time) of uncoated ordnance when exposed to pool fires have been reported by many investigators (References 9, 10, 11, 12, 13, and 14). Specifically, Hontgas (Reference 9) has reported a series of tests in which inert ordnance were

engulfed in pool fires and cooling was provided with water and AFFF using handlines and deck nozzles. Included in the documentation are the temperature history curves of various locations within the inert ordnance. Multiple parameters were varied in each test making it impossible to get correlation of the data at different coolant flow rates or handline locations relative to the ordnance. This study indicates that application of AFFF would not cool the ordnance until the fire had been extinguished.

Cragin, Pakulak and Vernon (Reference 10) calculated a heat transfer parameter from heated ordnance to water and AFFF using inside skin temperature of the ordnance. The procedure used during this study was to heat inert ordnance with a propane burner rack to a specified temperature, turn the burner rack off, and begin cooling. An extensive series of photographs was included in this report to document the effectiveness of the coolant coverage over the ordnance. They show that the most effective coverage of the ordnance is provided when the coolant is dispersed in a fog pattern. The study shows that AFFF cannot completely cover the surface of uncoated ordnance (especially the bottom of the back side), although it can cover coated ordnance. This study also concluded that if the fire engulfing a coated Mark 82 is extinguished within 7 minutes the ordnance will not cook off, even if uncooled.

C. TEST SETUP, INSTRUMENTATION, AND MATRIX

Testing was performed by suspending a calorimeter 0.91 meters above a pool of burning JP-4. The pool size area ranged from 91.4 m^2 to 274 m^2 .

The calorimeter consisted of three cylinders divided into five circumferential sections each. The cylinders and sections were thermally insulated from each other to allow quantification of the heat transfer rates to various areas of the calorimeter. Each of the circumferential sections in two of the three cylinders (the middle and one end cylinder) were instrumented with thermocouples to measure the transient temperatures experienced during the fire and subsequent cooling. The third section was not instrumented because it was symmetric with the first end section. The area with the highest heat flux is the bottom of the ordnance. Since it is not always possible to cover the bottom of the back side (the near side is

where the coolant stream was directed) of the ordnance with coolant, this area is of critical importance. This quadrant of the calorimeter was split to have two temperature measurements in this area. The construction of the calorimeters is shown in Figures 6 through 8.

Testing was first conducted using water, AFFF, and Halon 2402 to cool an uncoated calorimeter. The calorimeter was then coated with 0.406 cm of FM-26 and retested with water, AFFF, and liquid nitrogen. The temperatures were read by a datalogger at 5-second intervals and stored on floppy disks. The data were later reduced using a desk-top computer. All of the tests were filmed with a video camera. Table 2 shows the test matrix used to evaluate the various coolants.

TABLE 2. COOLING TEST MATRIX

Calorimeter Type	Coolant	Cooling Flow Rate	Application Method
uncoated	water ^a	341 L/min	stream
uncoated	water ^a	341 L/min	fog
uncoated	water ^a	170 L/min	fog
uncoated	AFFF ^a	341 L/min(water)	fog
uncoated	Halon 2402 ^b	2.5 kg/s	stream
coated	water ^a	341 L/min	fog
coated	water ^a	170 L/min	fog
coated	AFFF ^a	341 L/min(water)	fog
coated	liquid nitrogen ^c	---	---

^aThe water and AFFF were dispensed using a variable-cone, variable-flow-rate nozzle attached to a 3.81-cm handline.

^bThe Halon 2402 was dispensed from a pressurized system through a standard USAF 0.71-cm halon nozzle.

^cDuring the liquid nitrogen tests the Dewar was pressurized to 1000 kPa. The liquid discharge valve was then opened and the nitrogen flowed at whatever rate the Dewar could maintain. By the time the nitrogen reached the discharge of the feed pipe (1.83 meters long by 2.54 cm diameter), almost all of it had vaporized and the calorimeter was engulfed in vapor.

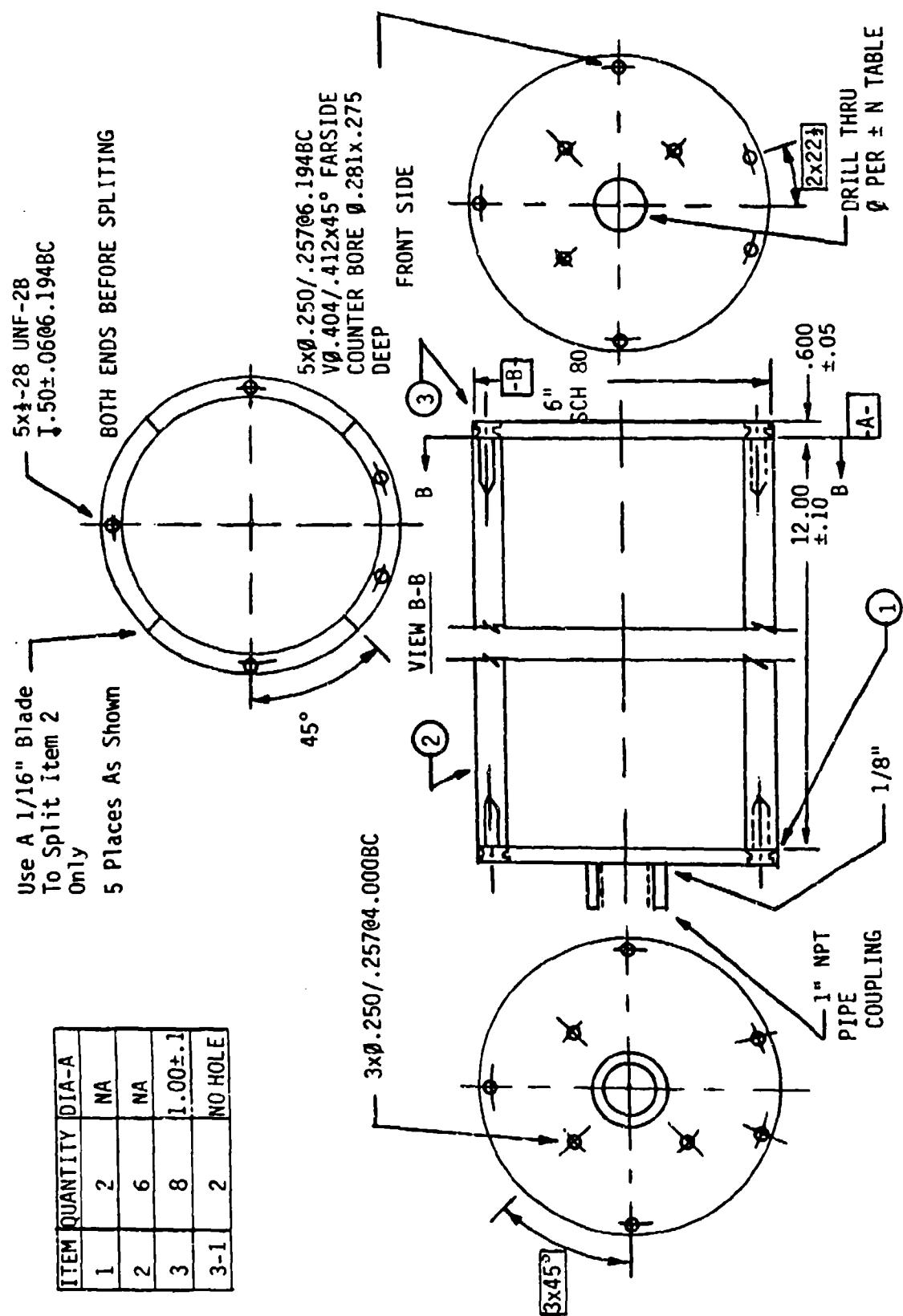
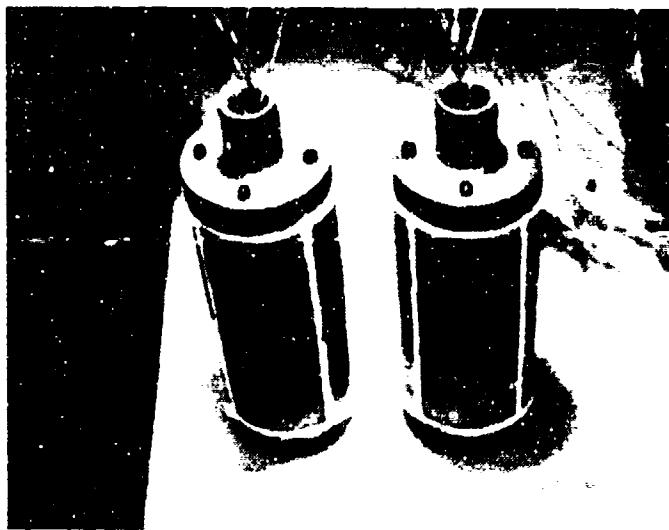


Figure 6. Calorimeter Engineering Drawing.

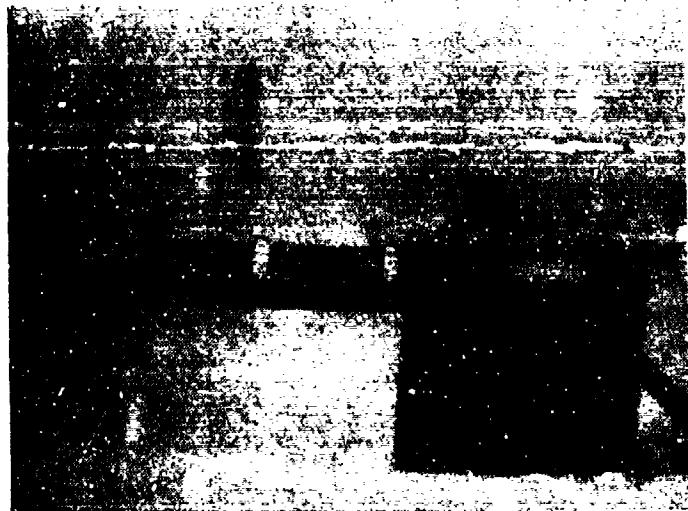


(a) Half-Scale Calorimeter.



(b) Calorimeter Thermocouple Placement.

Figure 7. Calorimeter Fabrication.



(a) Large-Scale Calorimeter on Test-Bed.



(b) Fire, Coolant, and Calorimeter Interaction.

Figure 8. Calorimeter Assembly and Testing.

D. OVERALL HEAT TRANSFER COEFFICIENT

The overall heat transfer coefficient can be calculated from equating the convective heat transfer with the conductive heat losses at the calorimeter surface;

$$U_{oa}(T_w - T_s) = K \frac{dT}{dr} \quad (16)$$

In Equation (16) the variable U_{oa} represents the overall heat transfer coefficient, and T_w and T_s are coolant and surface temperature, respectively. In the right-hand side, K is the thermal conductivity and $\frac{dT}{dr}$ is the spatial temperature gradient across the calorimeter wall and can be calculated from the Fourier Conduction Law. However, the total heat loss from the calorimeter during the cooling period is given by

$$q = \rho C_p \frac{\partial T}{\partial t} \quad (17)$$

where ρ and C_p are density and the heat capacity respectively, which are known quantities for the calorimeter. The term $\frac{\partial T}{\partial t}$ is the slope of the temperature history profile, which is known at any time. Since all parts of Equation (17) are known, the heat loss rate, q , can be calculated. Substituting q from Equation (17) into the Fourier Conduction Law, one obtains

$$q/A = K \frac{dT}{dr} \quad (18)$$

The left-hand side of Equation (18) is known and Equation (16) can be written as

$$U_{oa}(T_w - T_s) = K \frac{dT}{dr} = q/A \quad (19)$$

A computer program was written to calculate U_{oa} from the temperature history profiles and is presented in Appendix C.

Figure 9 illustrates the calorimeter's cross section and the location of thermocouples. The arrows specify the direction in which the coolant was applied. Effects of various coolants were tested experimentally. Figures 10 and 11 show typical temperature/time profiles for heating and cooling. In this case the cooling agent is water. The temperature profiles resulting from other coolants are given in Appendix D. Discussion of each coolant follows.

The test results showed that of the two water flow rates tested, the higher the water flow rate the more effective the cooling. The overall heat transfer coefficients for the different segments of the calorimeter for a water flow rate of 341 L/min ranged from 10^{-2} to 10^{-3} cal/cm² s K, while they ranged from 10^{-2} to 10^{-5} cal/cm² s K for a water flow rate of 170 L/min. This is reflected in the temperature profiles. The temperature profiles for the 341 L/min flow rate show an immediate and dramatic temperature reduction for all parts of the calorimeter (Figures D-1 and D-2). The temperature profiles for the 170 L/min flow rate show rapid and dramatic temperature reductions only at the point where the water struck the calorimeter (Figures 10, 11, D-3, and D-4). There was a delay in the onset of the temperature drop in other parts of the calorimeter and the temperature drop rate was not nearly as high as with the 341 L/min case. The cooling was ineffective on some parts of the calorimeter.

AFFF rapidly extinguished the fires during testing. It then cooled the calorimeters, although at a rate much lower than that of water (Figures D-5 through D-8). The AFFF was incapable of providing cooling to some parts of the calorimeter. The overall heat transfer coefficients for AFFF at 341 L/min ranged from 10^{-4} to 10^{-5} cal/cm² s K. The overall heat transfer coefficients for 170 L/min were similar.

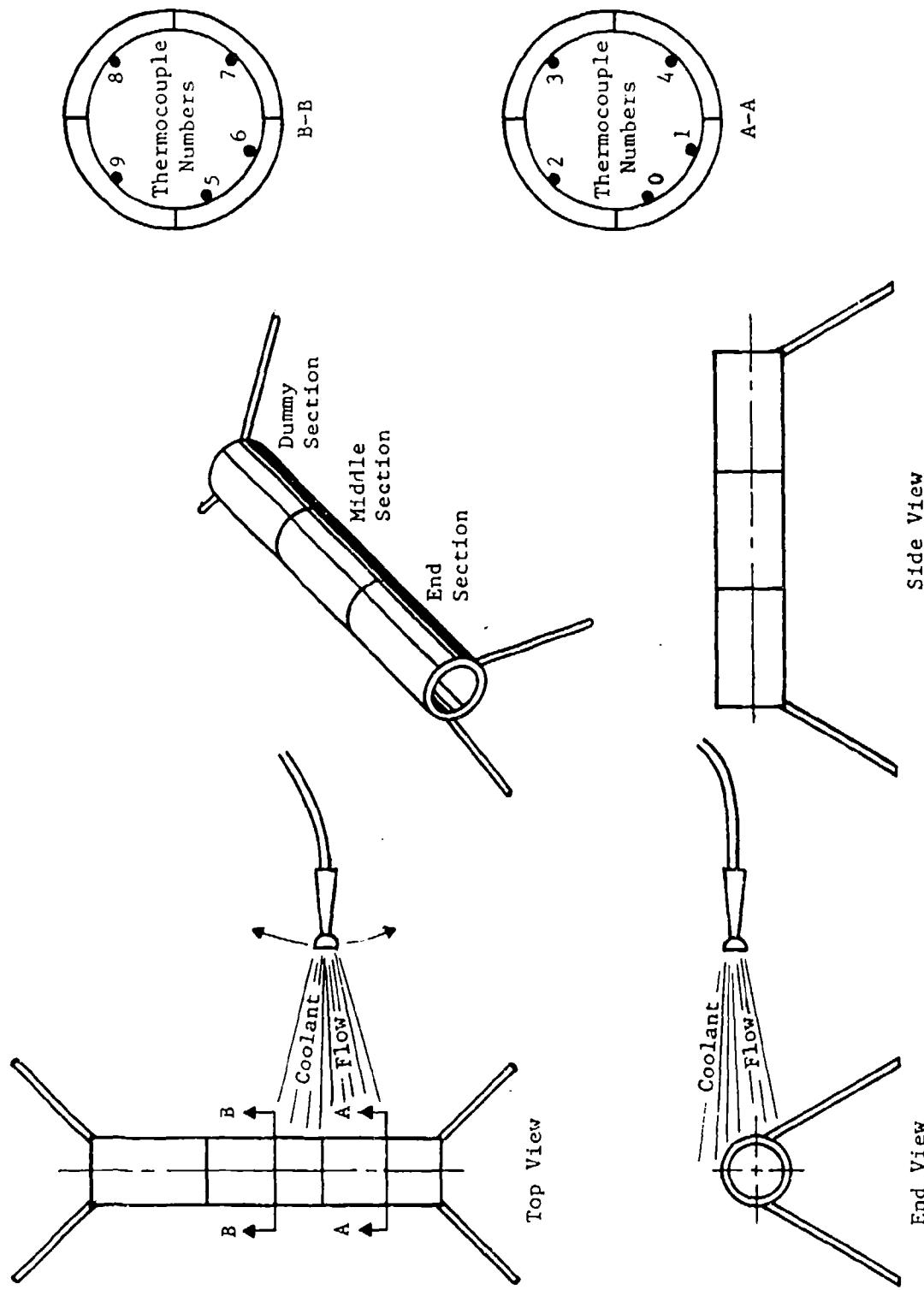


Figure 9. Calorimeter Test Configuration.

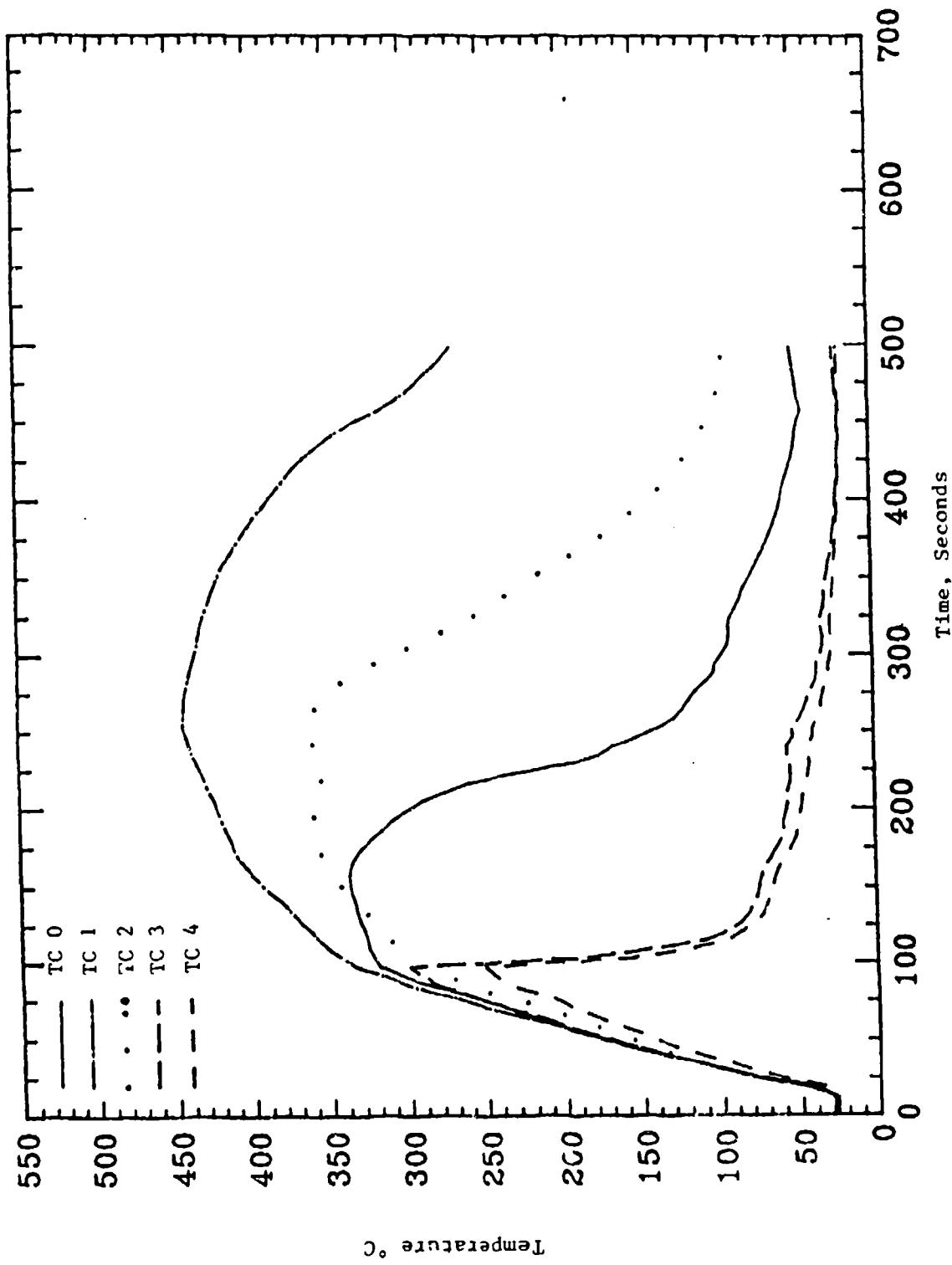


Figure 10. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

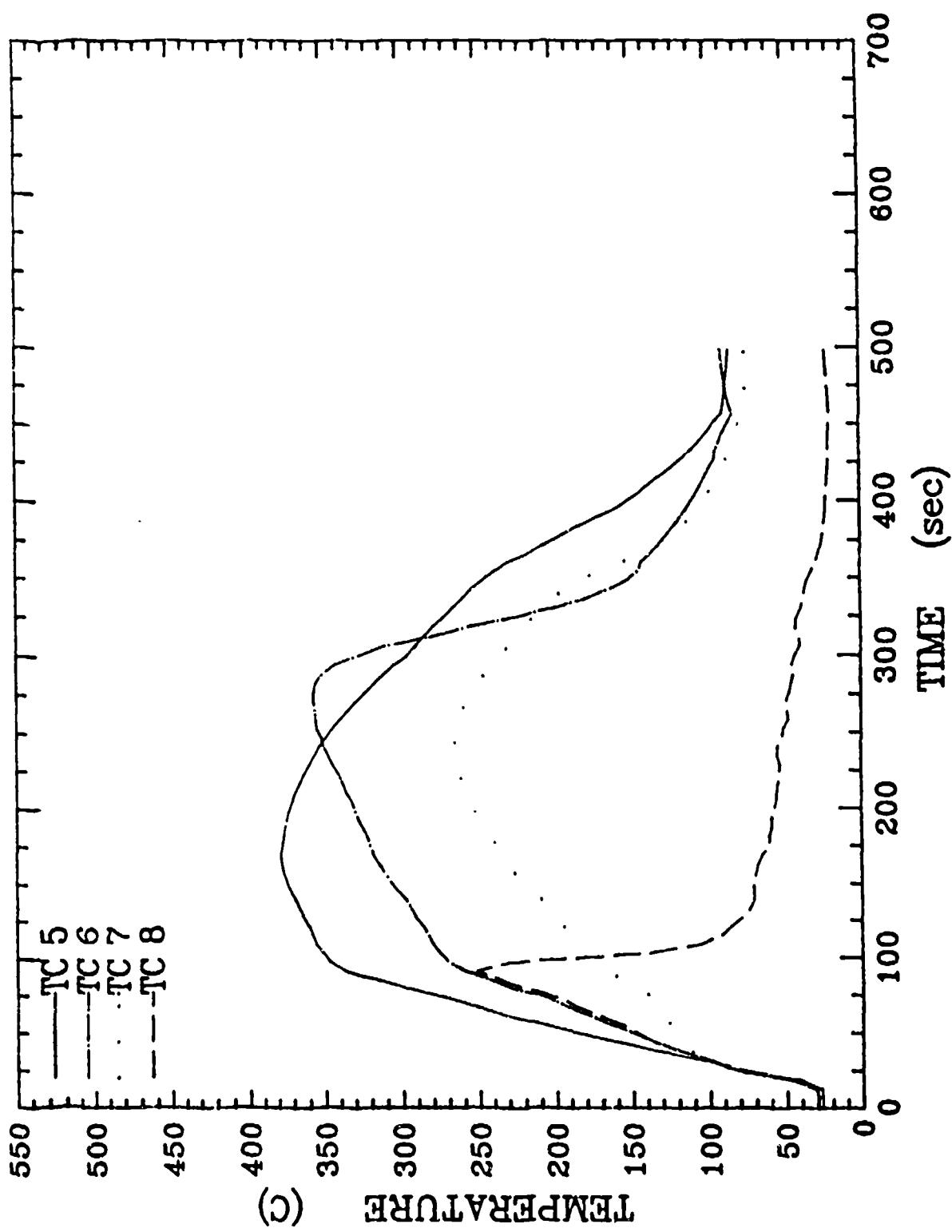


Figure 11. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

The Halon 2402 was ineffective as a coolant. It was able to stop the temperature rise at the points where it struck the calorimeter, but was unable to cool other areas (Figures D-9 and D-10). The overall heat transfer coefficients ranged from 0 to 10^{-4} cal/cm² s K. The Halon 2402 did not extinguish the fire since was not sprayed at the base.

The testing on coated calorimeters showed the remarkable insulating ability of the FM-26 coating. Before cooling was initiated, the temperature rise was a fraction of that for the uncoated calorimeter (Figures D-11 through D-14). The insulating ability of the FM-26 also dramatically slows down the rate of energy removal. The overall heat transfer coefficient with a water coolant flow rate of 341 L/min ranged from 10^{-3} to 10^{-4} cal/cm² s K.

The liquid nitrogen provided very effective cooling in the area where the nitrogen impinged on the calorimeter (Figure D-15). The fixed-pipe feed system for the liquid nitrogen did not allow it to be spread over the calorimeter surface, although the nitrogen did provide more effective cooling than the water on the impinged area. The overall heat transfer coefficients for the liquid nitrogen ranged from 10^{-2} to 10^{-5} cal/cm² s K.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Response of ordnance to accidental flame impingement was studied experimentally as well as numerically. Calculations were made to quantify the effect of the various coolants on cookoff times. Experiments were conducted to assess the fire interaction with ordnance to quantify effective coolant application rates, to evaluate various cooling agents, and to provide baseline heat transfer coefficients essential to cookoff prediction calculations.

Calculations show that extension of the cookoff time can be obtained when coolant is applied to the ordnance as long as the temperature of the explosive has not reached the critical point, that is, the point where an irreversible exothermic reaction begins. It is concluded that cookoff time extension strongly depends on the overall heat transfer coefficient and the cooling initiation time.

The effects of various coolants on cookoff time were evaluated experimentally. Water, AFFF, Halon 2402, and liquid nitrogen were investigated as cooling agents. Although AFFF does not cool as effectively as water, it extinguishes the fire while cooling the ordnance and may be considered a superior agent. Ordnance with intumescent coatings were compared with uncoated ordnance. Limited experimental data suggest that FM-26 coating is effective initially in preventing heat from transferring in, but, at the same time, the char layer formed when the coating is heated hinders removal of heat by the coolant and does not significantly alter the cookoff time.

It is recommended that additional studies be conducted to further evaluate the effectiveness of water and AFFF on cookoff time of coated ordnance in terms of the physical properties of various coating materials. This would require a combination of predictions using the computer codes developed and carefully instrumented tests using live ordnance.

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APPENDIX A
PROGRAM
FLOWCHART

MAD PROGRAM (REFERENCE 5)

SUBROUTINE

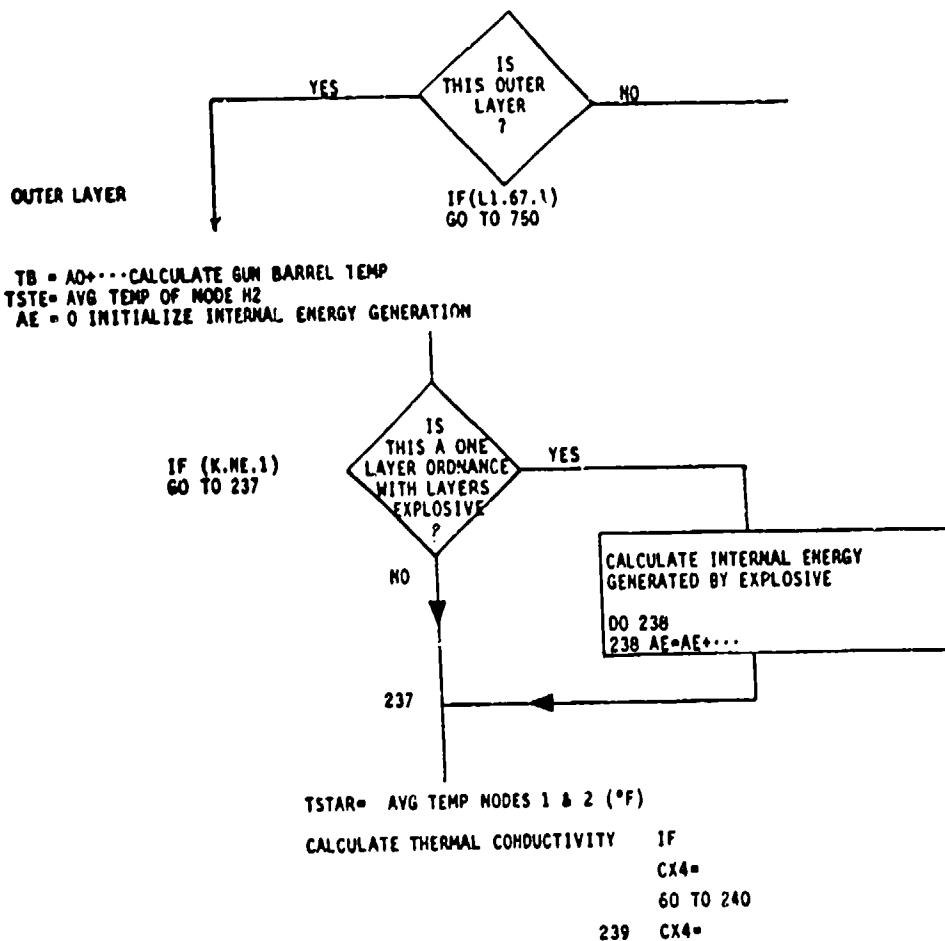
COMMON BLOCK

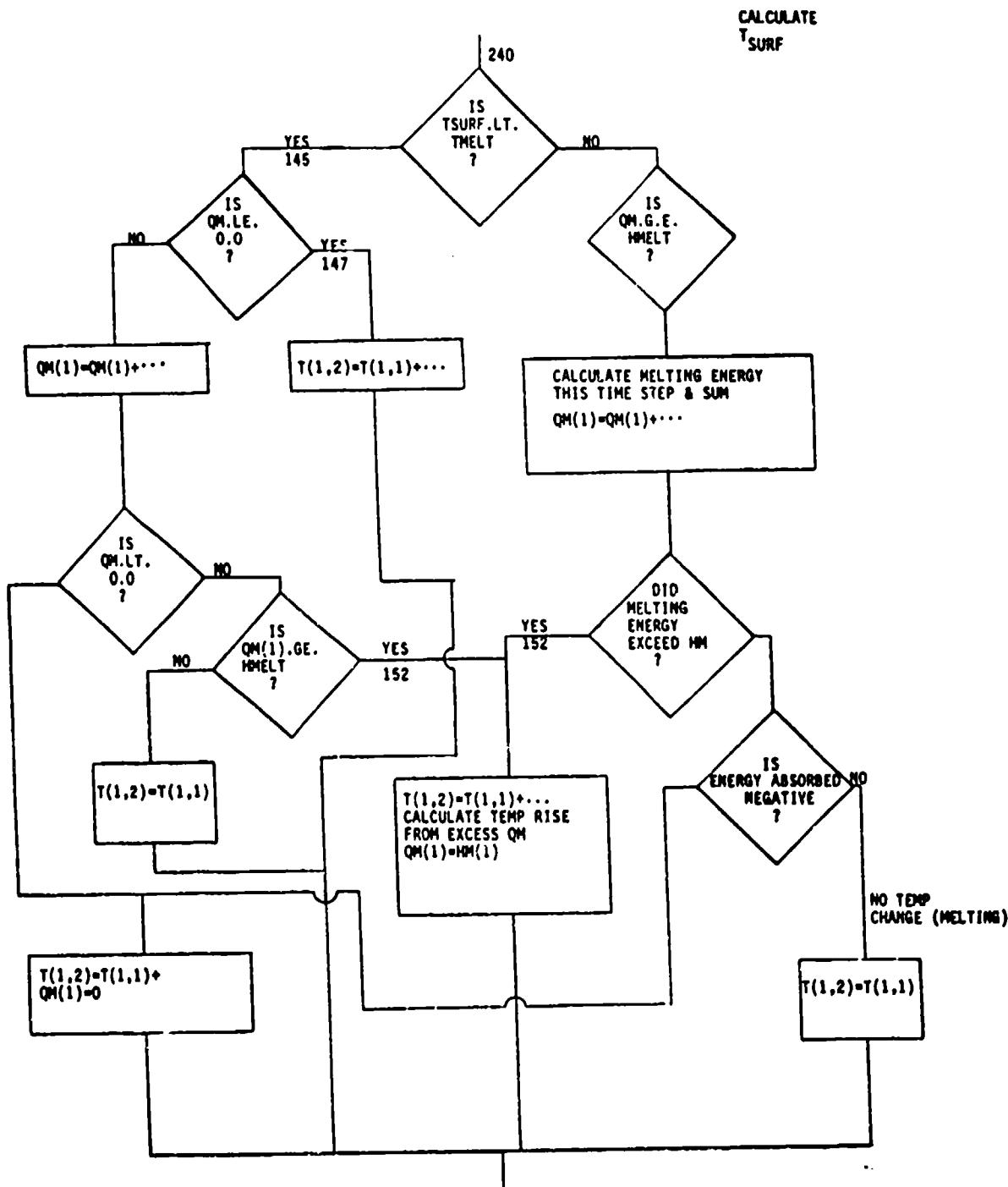
$F(X)$ = FUNCTION FOR THERMAL CONDUCTIVITY

$G(X)$ = FUNCTION FOR THERMAL CONDUCTIVITY

DO 250 L1=1,K DO LOOP ON # OF LAYER

L2=L1+1 L2 IS NEXT LAYER





750 CONTINUE

$M = M + IPT(L1)$

LAYER TEMPS

IS
THIS OUTER
LAYER
?

YES

121

CALCULATE LOWEST RATE
IN THIS LAYER
 $I=I+2$

TST1= CONVERT SURROUNDING
TST2= NODE TEMPS TO
TST3= °F

CALCULATE THERMAL CONDUCTIVITIES
AND FOURIER MODULII FOR
TST1&TST2

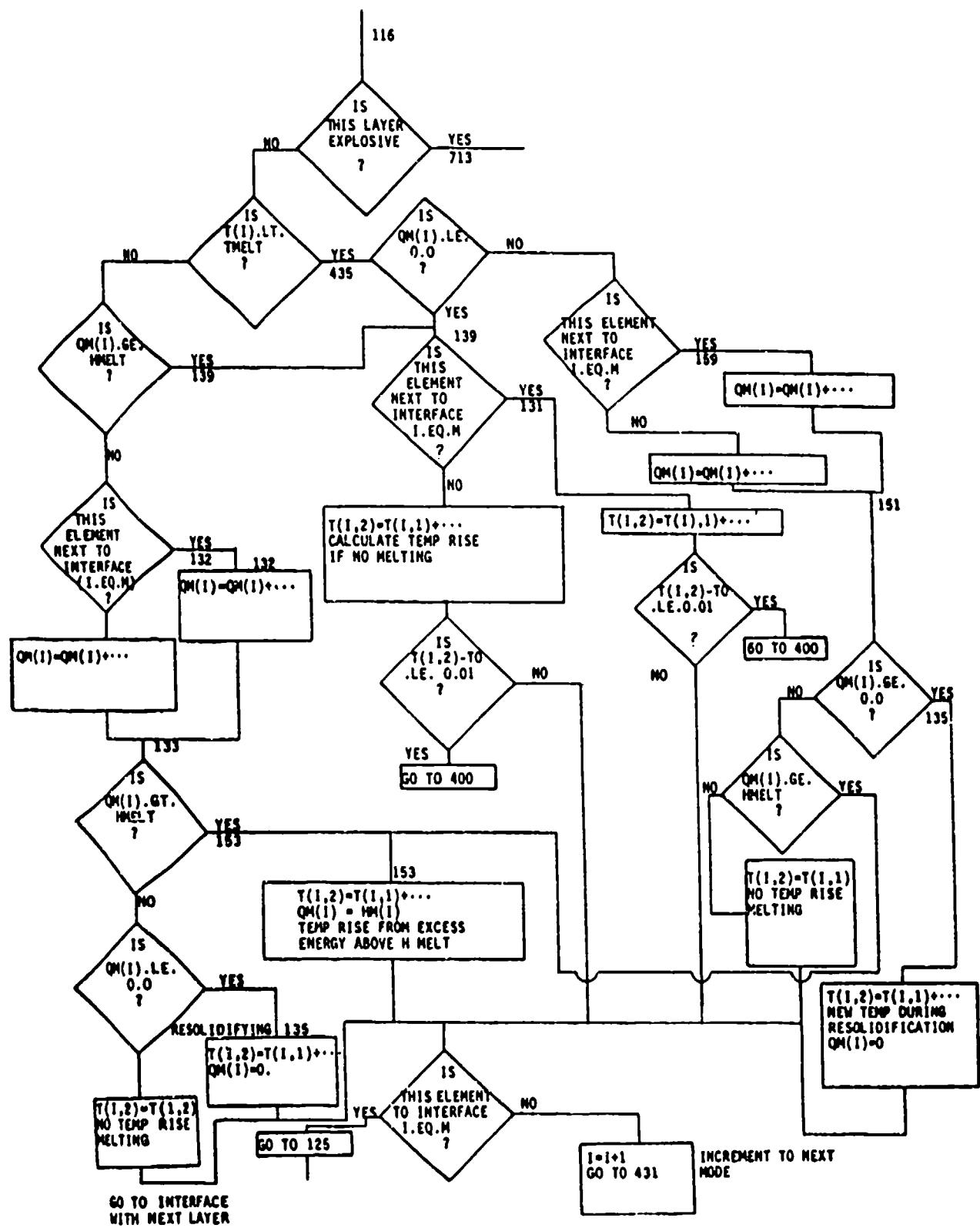
431

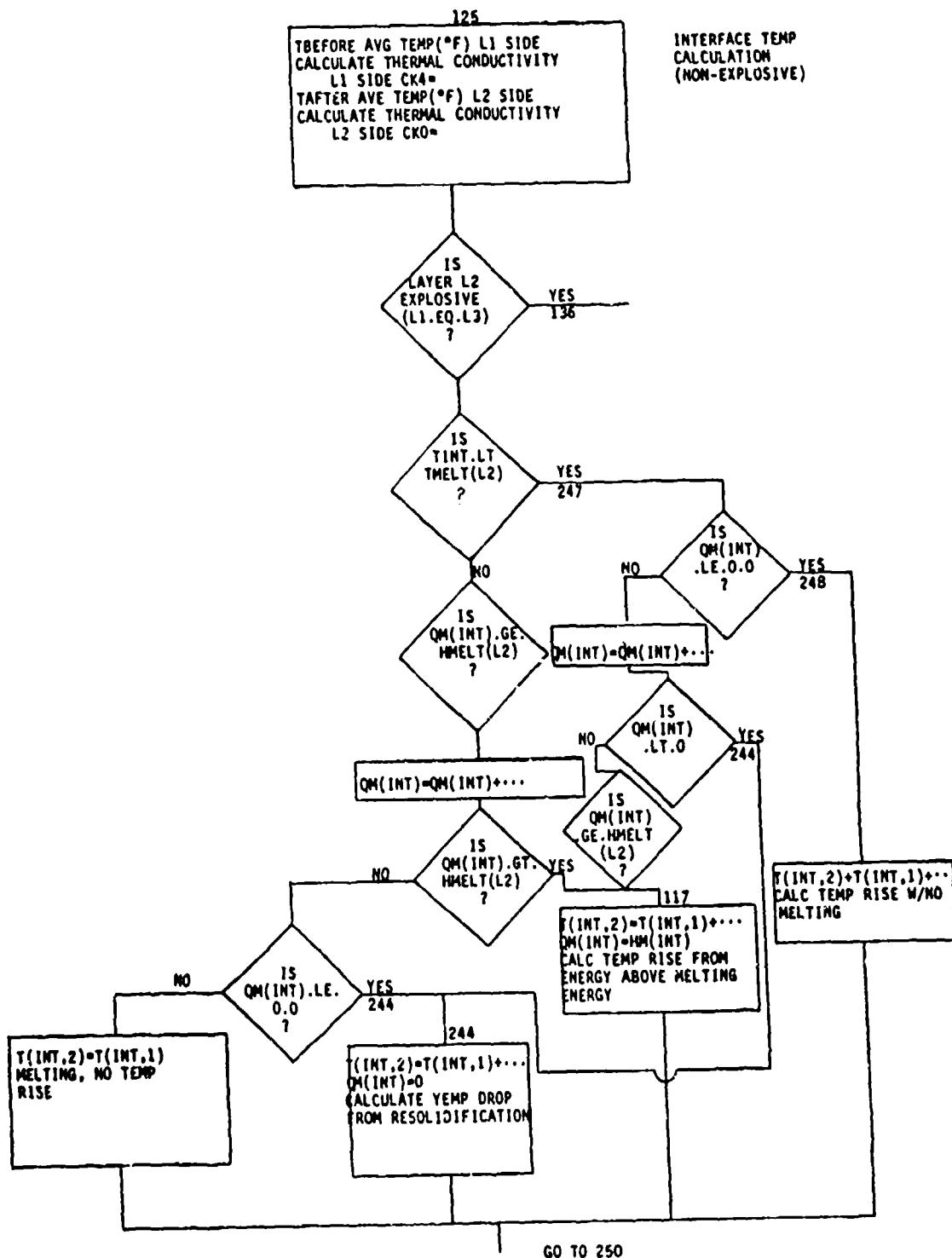
RESET THERMAL CONDUCTIVITIES
AND FOURIER MODULII FOR
NEXT NODE.

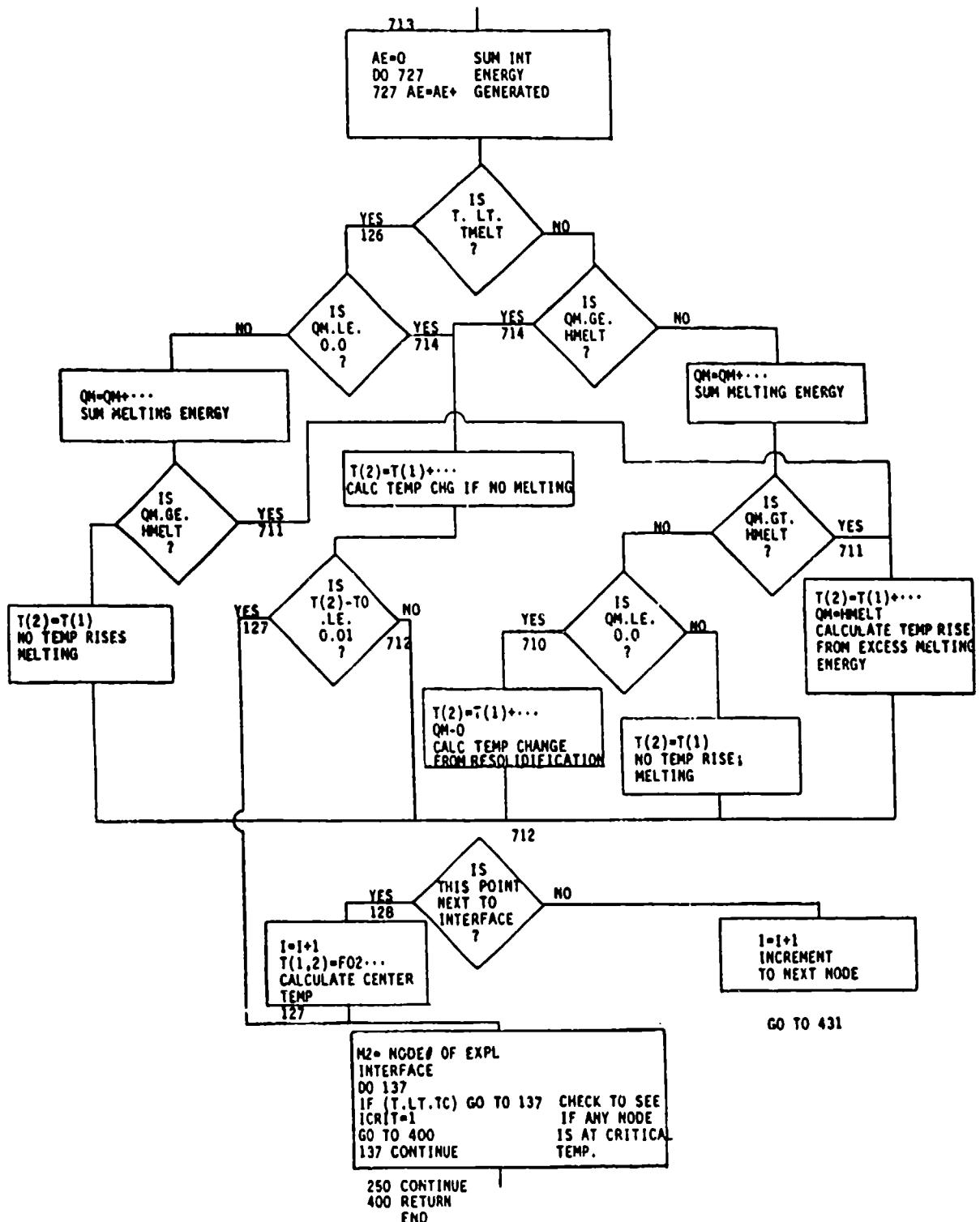
433

CALCULATE THERMAL CONDUCTIVITY
AND FOURIER MODULUS FOR TST3

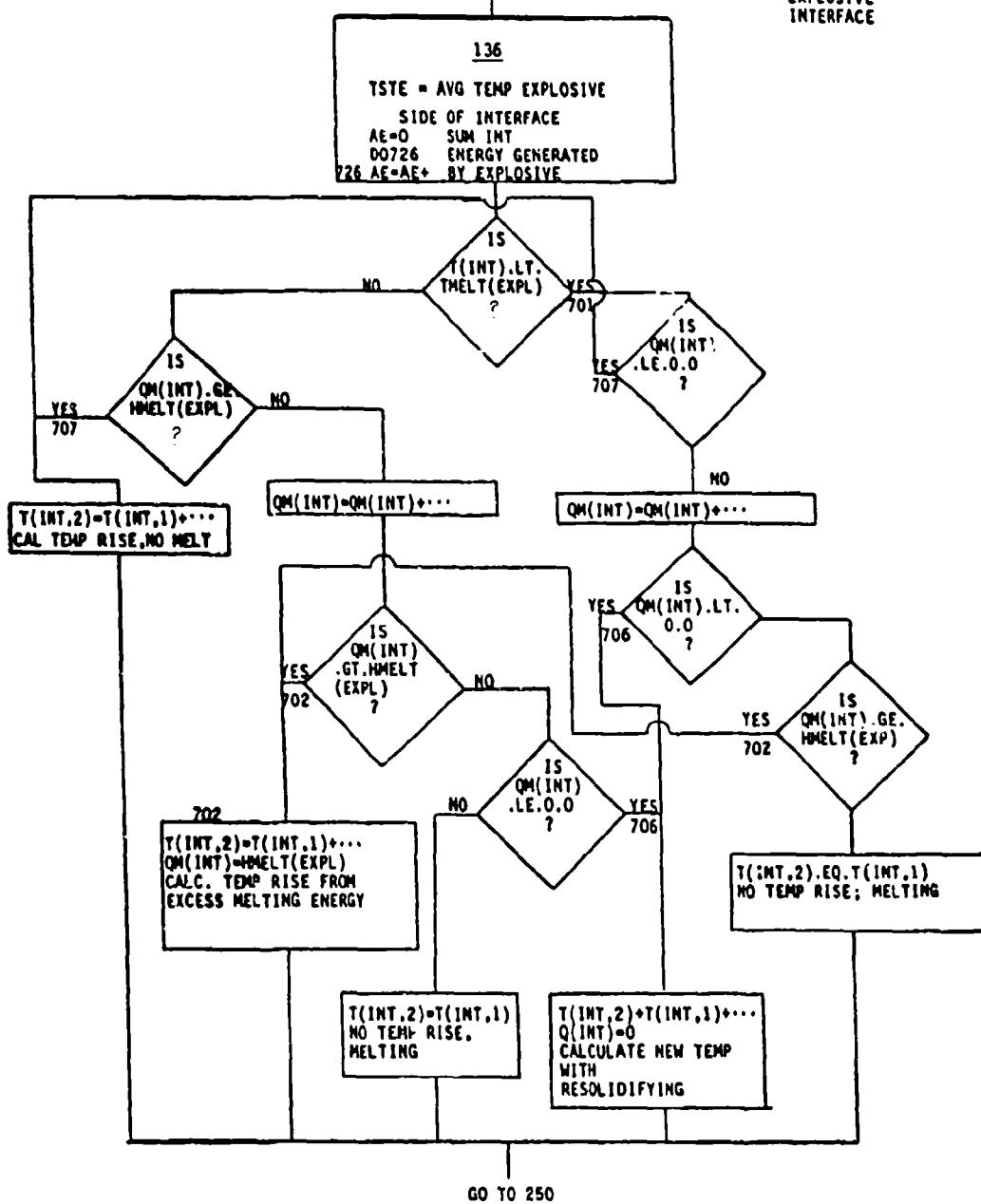
116







EXPLOSIVE
INTERFACE



APPENDIX B
PROGRAM LISTING

```

program mad
$storage:2
$nofloatcalls
    real hm,hml,hm2
    character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uoas,tw
iread = 0.
10 call readinpt(iread)
if ( k .eq. 0 ) go to 80
if ( irestart .ne. 1 ) go to 20
go to 30
20 call fourier
call initlize
c-----evaluate temperatures in layers and interfaces-----
    lpt = 1
30   do 60 mj=lpt,maxt
      i=2
      tim =tim+dt
      m=0
      call layer
      if (icrit .eq. 1) call prntcrit
      if (icrit .eq. 1) go to 70
c-----check for printout time-----
      if(amod(ctr,v)) 50,40,50
40   call prntrslt
50   ctr=ctr+1.
      do 60 iset=1,n
      t(iset,1)=t(iset,2)
60   continue
70   go to 10
80   stop
end
subroutine readinpt(iread)
character*64 file7, file6, file9
    character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uoas,tw

```

```

c-----read in computation requirements-----
c           k - number of layers, v - calc./printout
c           time - max. time for calc.
c           dt - time increment
if ( iread .ne. 0. ) go to 200
iread = 1.
write(*,100)
100 format(' Enter name of input data file: \'')
read(*,'(a)') file7
write(*,110)
110 format(' Enter name of file for output data: \'')
read(*,'(a)') file6
write(*,120)
120 format(' Enter name of restart data file: \'')
read(*,'(a)') file9
open(7,file=file7,status='old')
open(6,file=file6,status='new')
200   read(7,*) k, r
      if (k.eq.0) return
      read (7,*) irestart,icool,layout
      if ( irestart .ne. 1 ) go to 5
      open(9,file=file9,status='old')
      go to 8
5   open(9,file=file9,status='new')
8    read(7,1) (title(j),j=1,8)
      read(7,*) v, time, dt, inc
      do 10 j = 1,k
      read(7,1) matl(j)
10   read(7,*) dam(j),rho(j),c(j),kk(j),pt(j),hm(j),tm(j)
      do 20 j = 1, k
      read(7,*) cone(j),first(j),second(j),third(j),fourth(j)
      read(7,*) ctwo(j), fifth(j), sixth(j),tmid(j)
      read(7,*)cthree(j),sevnth(j),eighth(j),thigh(j)
20   continue
      read(7,*) t0,tc,epsilon,di,tflame,tbld
      rt = di / 2.
      read(7,1) explid
      read(7,1) weapid
      do 30 ki = 1,k
         j = 1
         read(7,*) e(ki,j),z(ki,j),xm(ki,j),q(ki,j)
      if (kk(ki) .eq. 0 ) go to 30
      do 25 j = 2, kk(ki)
25   read(7,*) e(ki,j),z(ki,j),xm(ki,j),q(ki,j)
      30 continue
      if ( icool .ne. 1) go to 40
      read(7,*) timcool,uoa,tw
40   if( irestart .ne. 1 ) return
      read(9,2) n,tim,maxt,lpt
      read(9,3) (t(l,1),l=1,n)
1   format (8a10)
2   format(lh ,i10,5x,f7.3,5x,i10,5x,i10)
3   format(lh ,8(1x,f9.5))
      return

```

```

end
subroutine initialize
    character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uoa,tw
    icrit =0
    ctr =0.0
    sigma = 1.356e-12
    maxt =ifix(time/dt)
    tim=dt
    l3 = k-1
    do 10 ml=1,l3
10    rcx(ml)=2.*dt/(rho(ml)*c(ml)*dx(ml)+rho(ml+1)*c(ml+1)*dx(ml+1))
    do 20 kl=1,k
        hml(kl)=rho(kl)*dx(kl)*.5*hm(kl)
20    hm2(kl) = 2.*hml(kl)
c-----evaluate radius at every point-----
    rad(1) = rt
    i5=1.
    i6=0.
    do 160 i4=1,k
        i6=ipt(i4)+i6
        do 165 mp=i5,i6
165    rad(mp+1)=rad(mp)-dx(i4)
160    i5=i6+1
c-----set temperatures initially to a constant-----
    do 201 init=1,n
        qm(init)=0.
        t(init,2)=t0
201    t(init,1)=t0
        do 1609 ii=1,20
1609    thighst(ii) = 0.0
    return
end
subroutine fourier
    character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uoa,tw

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c-----evaluate and stabilize fourier modulus-----
45   t1 = t0*1.8 -460.
      hc = 0.00134*(21.666/(rt*2.))**.195
      n=1.0
      do 15 j=1,k
         ck(j)=(cone(j)+first(j)*t1+second(j)*t1*t1+third(j)*t1*t1*t1+
1fourth(j)*(t1**4))/241.9
         alpha(j)=ck(j)/(rho(j)*c(j))
         ipt(j) = ifix(pt(j))
42   dx(j)=dam(j)/pt(j)
      if(dt.ne.0)go to 27
      do 28 ij=1,k
      if(ij.eq.1)go to 41
         ck(ij)=(cone(ij)+first(ij)*t1+second(ij)*t1*t1+third(ij)*t1*t1*t1+
1+fourth(ij)*(t1**4))/241.9
         alpha(ij)=ck(ij)/(rho(ij)*c(ij))
         ipt(ij)=ifix(pt(ij))
         dx(ij)=dam(ij)/pt(ij)
         d(ij)=0.2*(dx(ij)**2)/alpha(ij)
         go to 39
41   bi=hc*dx(1)/ck(1)
         d(ij)=0.5*(dx(1)**2)/((1.+bi)*alpha(1))
39   if(d(1).le.d(ij))go to 28
         d(1)=d(ij)
28   continue
         dt=d(1)
27   theta(j)=alpha(j)*dt/(dx(j)**2)
         rfk(j)=theta(j)/ck(j)
         if(j.eq.1) go to 20
         go to 21
20   bi=hc*dx(1)/ck(1)
         if(theta(1)-0.5/(1.+bi)) 112,112,22
21   if(theta(j).le.0.2) go to 112
22   theta(j)=0.75*theta(j)
         dx(j)=sqrt(alpha(j)*dt/theta(j))
         ipt(j)=ifix(dam(j)/dx(j))
         pt(j)=float(ipt(j))
         go to 42
112  n=n+ipt(j)
15   continue
      return
end
subroutine layer
      character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),l1,l2,l3,m,1,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,1,pt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ckl,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,b1,
& thighst(20),layout,irestart,icool,timcool,uoa,tw

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do 100 11=1,k
12 = 11 + 1
if ( 11 .gt. 1 ) go to 10
call tsurf
10 m = m + ipt(11)
if ( 11 .eq. 1 ) go to 20
i = i + 2
20 call thermppr
keyeqn = 0
if ( t(i,1) .lt. tm(11) ) keyeqn = 1
if ( qm(i) .ge. hm2(11) ) keyeqn = 1
call newtemp
dtmin = f02 * 0.01
if ( abs( t(i,2) - t(i,1) ) .le. dtmin ) go to 60
30 if ( i .eq. m ) go to 40
i = i + 1
go to 20
40 if( 11 .eq. k ) go to 50
call tintface
go to 60
c *** calculate temperature of center of bomb ****
50 i = i + 1
t(i,2) = f02 * ( ( dx(11)**2 ) * ae / ck2 + 2. * t(i-1,1) +
& ( 1. / f02 - 2. ) * t(i,1) )
c *** check to see if bomb has cooked off ****
60 if ( 11 .ne. k ) go to 100
m2 = m - ipt(11) + 1
do 70 11 = m2,m
if ( t(11,2) .lt. tc ) go to 70
icrit = 1
return
70 continue
100 continue
return
end
subroutine tsurf
character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icoool,timcool,uoa,tw
f(x,a,b,c,d,e) = ( a + b*x + c*x*x + d*x*x*x + e*(x**4) ) /241.9
g(x,a,b,c,d) = ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
zz(x,a,b,c) = ( a + b/(x*x) + c/(x**4) ) / 241.9
c *** calculate internal energy generated at surface ****
if ( tim .ge. tbld ) go to 5
tf = ( tflame - t0 ) * ( tim**3 / tbld**3 ) + t0
go to 7

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5 tf = tflame
7 tavg = ( t(1,1) + t(2,1) ) / 2.
ae = 0
do 10 ii = 1,kk(l1)
10 ae = ae + xm(l1,ii) * q(l1,ii) * z(l1,ii) *
& exp(-e(l1,ii))/(r*tavg)
ae = ae * rho(l1)
c *** calculate thermal properties of first two nodes *****
tlf = t(1,1) * 1.8 - 460.
t2f = t(2,1) * 1.8 - 460.
c *** account for reaction of ablative coating *****
if( layout .ne. 1 ) go to 14
if ( tlf .lt. thighst(1) ) go to 11
thighst(1) = tlf
go to 12
11 tlf = thighst(1)
12 if (t2f .lt. thighst(2) ) go to 13
thighst(2) = t2f
go to 14
13 t2f =thighst(2)
14 avgts = ( tlf + t2f ) / 2.
if ( avgts .ge. tmid(l1) ) go to 16
cka = f(avgts,cone(l1),first(l1),second(l1),third(l1),fourth(l1))
go to 20
16 if ( avgts .ge. thigh(1) ) go to 18
cka = zz( avgts, ctwo(l1), fifth(l1), sixth(l1) )
go to 20
18 cka = g(avgts,cthree(l1),sevnth(l1),thigh(l1),eighth(l1))
c *** branch to proper temperature calculation *****
20 if ( t(l1,1) .lt. tm(l1) ) go to 30
if ( qm(l1) .ge. hml(l1) ) go to 30
c *** melting temperature and energy calculation *****
if ( icool .ne. 1 .or. tim .lt. timcool ) go to 25
qm(l1) = qm(l1) + dt * dx(l1) * ae / 2. +dt * ( uoa * (tw - t(l1,1))-
2 (rt - dx(l1) / 2.) * cka * ( t(l1,1) - t(2,1) ) / ( dx(l1) * rt ) )
go to 28
25 qm(l1) = qm(l1) + dt * dx(l1) * ae / 2. +dt * ( hc * (tf - t(l1,1))+
1 epsilon * sigma * ( tf**4 - t(l1,1)**4 ) -
2 (rt - dx(l1) / 2.) * cka * ( t(l1,1) - t(2,1) ) / ( dx(l1) * rt ) )
28 if ( qm(l1) .gt. hml(l1) ) go to 40
if ( qm(l1) .lt. 0.0 ) go to 50
t(l,2) = t(l,1)
return
c *** calculate new temp rise from external heat fluxes *****
30 if ( icool .ne. 1 .or. tim .lt. timcool ) go to 35
t(l,2) = t(l,1) + rfk(l1) * ( dx(l1)**2 ) * ae +
& 2. * rfk(l1) * ( rt * dx(l1) * ( uoa * ( tw - t(l1,1) ) ) ) -
& ( rt - dx(l1) / 2.) * cka * ( t(l1,1) - t(2,1) )/( rt - dx(l1)/4.)
return
35 t(l,2) = t(l,1) + rfk(l1) * ( dx(l1)**2 ) * ae +
& 2. * rfk(l1) * ( rt * dx(l1) * ( hc * ( tf - t(l1,1) ) +
& epsilon * sigma * ( tf**4 - t(l1,1)**4 ) ) ) -
& ( rt - dx(l1) / 2.) * cka * ( t(l1,1) - t(2,1) )/( rt - dx(l1)/4.)
return

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c *** calculate temp rise from excess energy above melting energy ***
40 t(1,2) = t(1,1) + 2. * ( qm(1) - hml(1) ) / ( rho(1) * c(1)*dx(1))
  qm(1) = hm(1)
  return
c*** calculate temp drop from endothermic reaction ****
50 t(1,2) = t(1,1) + 2. * qm(1) / ( rho(1) * c(1) * dx(1) )
  qm(1) = 0.0
  return
end
subroutine thermprp
  character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
  & kk(5),l1,l2,l3,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
  & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
  & v,time,t0,jjj(16)
common / tp / ckl,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
  & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
  & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
  & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
  & thighst(20),layout,irestart,icool,timcool,uo,a,tw
f(x,a,b,c,d,e) = ( a + b*x + c*x*x + d*x*x*x + e*(x**4) ) / 241.9
g(x,a,b,c,d) = ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
zz(x,a,b,c) = ( a + b/(x*x) + c/(x**4) ) / 241.9
c *** this subroutine calculates thermal conductivities (ck),
c *** fourier modulii (fox) for each node point and
c *** internal energy generation (ae) for the current calculation node.
if ( keytherm .ne. 0 ) go to 50
temp1 = t(i-1,1) * 1.8 - 460.
temp2 = t(i,1) * 1.8 - 460.
if ( l1 .ne. 1 .or. layout .ne. 1 ) go to 6
if ( temp1 .le. thighst(i-1) ) go to 4
thighst(i-1) = temp1
go to 6
4 temp1 = thighst(i-1)
6 if ( temp1 .ge. tmid(l1) ) go to 8
  ckl = f(temp1,cone(l1),first(l1),second(l1),third(l1),fourth(l1))
  go to 20
8 if ( temp1 .ge. rhigh(l1) ) go to 10
  ckl = zz( temp1, ctwo(l1), fifth(l1), sixth(l1) )
  go to 20
10 ckl = g(temp1,cthree(l1),sevnth(l1),thigh(l1),eighth(l1))
20 f01 = rfk(l1) * ckl
  if ( l1 .ne. 1 .or. layout .ne. 1 ) go to 23
  if ( temp2 .le. thighst(i) ) go to 22
  thighst(i) = temp2
  go to 23
22 temp2 = thighst(i)
23 if ( temp2 .ge. tmid(l1) ) go to 25
  ck2 = f(temp2,cone(l1),first(l1),second(l1),third(l1),fourth(l1))
  go to 40
25 if ( temp2 .ge. rhigh(l1) ) go to 30
  ck2 = zz( temp2, ctwo(l1), fifth(l1), sixth(l1) )
  go to 40

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30 ck2 = g(temp2,cthree(11),sevnth(11),thigh(11),eighth(11))
40 f02 = rfk(11) * ck2
    go to 60
50 ck1 = ck2
    ck2 = ck3
    f01 = f02
    f02 = f03
60 ae = 0.
    do 70 ii = 1,kk(11)
70 ae = ae + xm(11,ii) * q(11,ii) * z(11,ii) *
     & exp(-e(11,ii)/(r*t(i,1)))
    ae = ae * rho(11)
    temp3 = t(i+1,1) * 1.8 - 460.
    if ( 11 .ne. 1 .or. layout .ne. 1 ) go to 76
    if ( temp3 .le. thighst(i+1) ) go to 74
    thighst(i+1) = temp3
    go to 76
74 temp3 = thighst(i+1)
76 if ( temp3 .ge. tmid(11) ) go to 78
    ck3 =f(temp3,cone(11),first(11),second(11),third(11),fourth(11))
    go to 90
78 if ( temp3 .ge. thigh(11) ) go to 80
    ck3 = zz( temp3, ctwo(11), fifth(11), sixth(11) )
    go to 90
80 ck3 = g(temp3,cthree(11),sevnth(11),thigh(11),eighth(11))
90 f03 = rfk(11) * ck3
    return
end
subroutine newtemp
    character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
     & kk(5),ll,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
     & ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
     & v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
     & c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
     & sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
     & ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
     & thighst(20),layout,irestart,icool,timcool,uo,a,tw
    if ( keyeqn .ne. 0 ) go to 30
c *** calculate melting energy and new temperature if finishes melting
    qm(i) = qm(i) + dt * ( ( ck2 + .25 * ( ck1 - ck3 ) ) *
     & ( rad(i) + .5 * dx(11) ) * ( t(i-1,1) - t(i,1) ) -
     & ( ck2 - .25 * ( ck1 - ck3 ) ) * ( rad(i) - .5 * dx(11) ) *
     & ( t(i,1) - t(i+1,1) ) ) / ( rad(i) * dx(11) ) + dt * dx(11) * ae
    if ( qm(i) .gt. hm2(11) ) go to 10
    if ( qm(i) .lt. 0.0 ) go to 20
    t(i,2) = t(i,1)
    return
10 t(i,2) = t(i,1) + ( qm(i) - hm2(11) ) / ( rho(11) * c(11)*dx(11) )
    qm(i) = hm2(11)
    return
20 t(i,2) = t(i,1) + qm(i) / ( rho(11) * c(11) * dx(11) )

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qm(i) = 0.0
return
30 t(i,2) = t(i,1) + ( ( f02 + .25 * ( f01 - f03 ) ) *
& ( rad(i) + .5 * dx(11) ) * ( t(i-1,1) - t(i,1) ) -
& ( f02 - .25 * ( f01 - f03 ) ) * ( rad(i) - .5 * dx(11) ) *
& ( t(i,1) - t(i+1,1) ) ) / rad(i) + rfk(11) * ae * ( dx(11)**2 )
return
end
subroutine tintface
character*10 matl(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uo,a,tw
f(x,a,b,c,d,e) = ( a + b*x + c*x*x + d*x*x*x + e*x**4 ) / 241.9
g(x,a,b,c,d) = ( a + b*( 1. - exp((c-x)/d) ) ) / 241.9
zz(x,a,b,c) = ( a + b/(x*x) + c/(x*x*x) ) / 241.9
c *** calculate thermal and heat generation properties *****
tbfor = ( ( t(m,1) + t(m+1,1) ) / 2. ) * 1.8 - 460.
if ( tbfor .ge. tmid(11) ) go to 5
ck4 = f(tbfor,cone(11),first(11),second(11),third(11),fourth(11))
go to 20
5 if ( tbfor .ge. thigh(11) ) go to 10
ck4 = zz ( tbfor, ctwo(11), fifth(11), sixth(11) )
go to 20
10 ck4 = g(tbfor,cthree(11),sevnth(11),thigh(11),eighth(11))
20 aebfor = 0.
do 30 ii=1,kk(11)
30 aebfor = aebfor + xm(11,ii) * q(11,ii) * z(11,ii) *
& exp(-e(11,ii)/(r*tbfor))
aebefor = aebefor * rho(11)
tafter = ( ( t(m+1,1) + t(m+2,1) ) / 2. ) * 1.8 - 460.
if ( tafter .ge. tmid(12) ) go to 35
ck0=f(tafter,cone(12),first(12),second(12),third(12),fourth(12))
go to 50
35 if ( tafter .ge. thigh(12) ) go to 40
ck0 = zz ( tafter, ctwo(12), fifth(12), sixth(12) )
go to 50
40 ck0 = g(tafter,cthree(12),sevnth(12),thigh(12),eighth(12))
50 aeafr = 0.
do 60 ii = 1,kk(12)
60 aeafr = aeafr + xm(12,ii) * q(12,ii) * z(12,ii) *
& exp(-e(12,ii)/(r*tafter))
aeafr = aeafr * rho(12)
c *** branch to proper equation to calculate new temperature *****
if ( t(m+1,1) .lt. tm(12) ) go to 90
if ( qm(m+1) .gt. hm(12) ) go to 100
c *** calculate melting energies *****

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qm(m+1) = qm(m+1) + dt *
& (ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11) -
& ck0 * (rad(m+1) - .5 * dx(12)) * (t(m+1,1) - t(m+2,1)) / dx(12)
& + ( rad(m+1) - .25 * dx(12) ) * dx(12) * .5 * aeafr ) / rad(m+1)
if ( qm(m+1) .gt. hml(12) ) go to 70
if ( qm(m+1) .lt. 0.0) go to 80
t(m+1,2) = t(m+1,1)
return
c *** calculate temperature rise from excess energy above melting energy
70 t(m+1,2) = t(m+1,1) + ( qm(m+1) - hml(12) ) * rcx(11) / dt
qm(m+1) = hml(12)
return
c *** calculate temperature drop from resolidification ****
80 t(m+1,2) = t(m+1,1) + qm(m+1) * rcx(11) / dt
qm(m+1) = 0.
return
90 if ( qm(m+1) .le. 0.0 ) go to 100
c *** calculate melting energy ****
qm(m+1) = qm(m+1) + dt *
& (ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11) -
& ck0 * (rad(m+1) - .5 * dx(12)) * (t(m+1,1) - t(m+2,1)) / dx(12)
& + ( rad(m+1) - .25 * dx(12) ) * dx(12) * .5 * aeafr ) / rad(m+1)
if ( qm(m+1) .lt. 0.0 ) go to 80
if ( qm(m+1) .ge. hml(12) ) go to 70
t(m+1,2) = t(m+1,1)
return
c *** calculate temperature rise (no melting or re-solidification) ****
100 t(m+1,2) = t(m+1,1) + rcx(11) *
& ( ck4 * (rad(m+1) + .5 * dx(11)) * (t(m,1) - t(m+1,1)) / dx(11)
& -ck0 * (t(m+1,1) - t(m+2,1)) * (rad(m+1) - .5 * dx(12)) / dx(12)
& + ( rad(m+1) - .25 * dx(12) ) * aeafr * .5 * dx(12) ) / rad(m+1)
return
end
subroutine prntrslt
character*10 matl(5),explid,weapid,title(8)
dimension b(16),pos(16)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,matl,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ck1,ck2,ck3,f01,f02,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tfblade,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,b1,
& thighst(20),layout,irestart,icoool,timcool,uoa,tw
c-----output point control      j(1) thru j(16)-----
if ( ctr .ne. 0 ) go to 167
jjj(1)=1
do 839 m6=2,16
jjj(m6)=jjj(m6-1)+inc
839 continue
write(6,1) (title(ilp),ilp=1,8)
1 format(8a10)

```

```

write(6,10) explid,weapid,rt
write(6,18) dt
write(6,106)
write(6,17)
write(6,23)
do 171 i9=1,k
write(6,19) i9,matl(i9),dam(i9),pt(i9),dx(i9),rho(i9),c(i9),
lck(i9),alpha(i9),theta(i9),tm(i9),hm(i9)
171 continue
write(6,24)
24 format(1h0,70hconductivity equations (temp. coeff. units in "f ,
lck(i) units in "k"))
do 172 i7=1,k
write(6,32)i7,cone(i7),first(i7),second(i7),third(i7),fourth(i7)
172 continue
32 format(1h0,3hck(.i2,5h) = (.f10.4,2h -,e13.5,4h*t +,e13.5,6h*t*t -
1,e13.5,8h*t*t*t +,e13.5,16h*(t**4)) / 241.9)
write(6,26)
26 format(//20h boundary conditions)
write(6,34)
write(6,35)t0,epsilon,hc,tc
35 format(1h ,3x,f7.1,9x,f5.2,8x,f8.5,6x,f8.1)
34 format(1h0,12hinitial temp,5x,7hepsilon,
15x,12hconvec coeff,5x,9hcrit temp/3x,7h(deg k),19x,
215h(cal/sec-cm2-k),7x,3h(k))
if ( icool .ne. 1 ) go to 341
write (6,342)
342 format(//1h ,12hTime Cooling,12x,8huoa,13x,6htw,
&/1h ,12hStarts (sec),9x,15h(cal/cm2-sec-K),9x,7h(deg K))
write(6,343) timcool,uo,tw
343 format(1h ,3x,f5.1,16x,f8.6,13x,f5.1)
341 write(6,33)
write(6,36) v,time,dt
if(k.eq.1) go to 86
do 85 m2=1,13
m3 = m2 + 1
85 write(6,31) ..2..m3 ,rif
86 continue
33 format(// 21h interface properties,45x,22hcomputation parameters)
36 format(1h0,3x,8hlocation,12x,12hconductivity,30x,4hv = ,f10.6,2x,
17htime = ,f7.2,2x,5hdt = ,f12.8/15h (between yrs),12x,6hcoeff./)
31 format(1h ,3x,2(i3),18x,f6.4)
write(6,37)
do 999 k9 = 1,k
write(6, 113) k9, kk(k9)
113 format(1h , 'layer number ',i1,5x,18hnumber ind. comps.,19x,i3//)
write(6,107) (e(1:k9,k5),k5=1,kk(k9))
107 format(1h0,30hactivation energy (cal/mole) ,5(1x,e15.5))
write(6,108) (z(k9,k5),k5=1,kk(k9))
108 format(1h ,30hcollision number (1./sec) ,5(1x,e15.5))
write(6,109) (xm(k9,k5),k5=1,kk(k9))
109 format(1h ,13hmass fraction,17x,5(6x,f10.5))
write(6, 110) (q(k9,k5),k5=1,kk(k9))
110 format(1h ,30hheat of reaction (cal/gm) ,5(6x,f10.5))

```

```

999  continue
      write(6,11)
      do 111 j7=1,16
         j6=jjj(j7)
111   pos(j7)=rad(1)-rad(j6)
      write(6,12)  (pos(j6),j6=1,16)
167   continue
      do 168 i8=1,16
         j1=jjj(i8)
168   b(i8)=t(j1,1)
      write(6,13) tim,tf,(b(i8),i8=1,16)
      write(9,1013) n,tim,maxt,mj
      write(9,1014) (t(l,2),l=1,n)
1013  format(1h ,i10,5x,f7.3,5x,i10,5x,i10)
1014  format(1h ,8(1x,f9.5))
      rewind (9)
11   format(62h1the following table is a temperature history of the exp
11  llosive//)
12   format(12h depth (cm.),5x,16(2x,f5.2)//3x,10htime free/2x,13h(sec
11 .) stream/9x,5hflame/9x, 8htemp("k")//)
13   format(1h ,f7.2,2x,f6.1,1x,16(1x,f6.1))
17   format(1h0,127hlayer material thickness pts dx density s
1pec.heat therm. con. alpha fourier mod. melt.temp. heat
2 of fusion)
23   format(1h ,18x,5h(cm.),10x,5h(cm.),2x,7h(gm/cc),2x,26h(cal/gm "k)(
1cal/sec cm "k),11h(cm*cm/sec),18x,4h("k),9x,8h(cal/gm)//)
10   format(1h0,2x,24hexplosive identification,a10//2x,
121hweapon identification,4x,a10//2x,9hradius = ,
2f10.6,4h cm.)
18   format(1h0,2x,16htime increment -,f7.5,2x,3hsec)
19   format(1h ,i3,3x,a10,1x,f7.4,1x,f5.1,1x,f7.5,2x,f7.4,1x,2(3x,f7.5,
14x ),2(2x,f6.3,4x),2x,f7.2,7x,f7.3)
37   format(///21h explosive properties)
106  format(///20h material properties)
      return
      end
      subroutine prntcrit
      dimension zx(16),b(16)
      character*10 mat1(5),explid,weapid,title(8)
common / a / t(1000,2),tm(5),qm(1000),hm(5),hml(5),hm2(5),k,
& kk(5),11,12,13,m,i,pt(5),ipt(5),rad(1000),d(5),keyeqn,icrit,
& ctr,maxt,dx(5),dam(5),n,lpt,weapid,explid,mat1,inc,r,title,
& v,time,t0,jjj(16)
common / tp / ckl,ck2,ck3,f01,f02,f03,rfk(5),rcx(5),alpha(5),
& c(5),cone(5),cthree(5),first(5),second(5),third(5),fourth(5),
& sevnth(5),eighth(5),ctwo(5),fifth(5),sixth(5),tmid(5),thigh(5),
& ae,rho(5),xm(5,5),q(5,5),e(5,5),z(5,5),keytherm,theta(5),ck(5)
common / bc / tflame,tf,epsilon,sigma,tc,tim,dt,tbld,hc,rt,bi,
& thighst(20),layout,irestart,icool,timcool,uoa,tw
      do 10 jj=1,16
         j1=jjj(jj)
         zx(jj)=t(j1,1)
10   b(jj)=t(j1,2)
      timb=tim-dt

```

```
      write(6,20) timb,tf,(zx(i8),i8-1,16)
      write(6,20) tim,tf,(b(i8),i8-1,16)
      write(6,30) rad(k3),tim,timb
20   format(1h ,f7.2,2x,f6.1,1x,16(1x,f6.1))
30   format(//65h a critical temp has been reached within the explosive
           le at radius-,f5.2,18h and between time-,f7.2,4h sec,10h and time-,
           2f7.2,4h sec)
           return
end
```

APPENDIX C
PROGRAM HTCOEFF

```

program htcoeff
dimension tcool(5), temp1(5), temp2(5), uoa(5)
character*1 answer
character*15 file5, file6
c *** layer 1 is the steel, layer 2 is the FM-26 (if app) ****
data rhocpl / 1.069 /, ckl / 0.109 /, ck2 / 3.5E-04 /
data drl / 0.432 /, dr2 / 0.406 /
data tcool / 63., 91., 21., 113., -118. /
      write(*,5)
5  format(' Enter name of input data file: \'')
read(*,'(a)') file5
write(*,6)
6  format(' Enter name of output data file: \'')
read(*,'(a)') file6
open(5,file=file5)
open(6,file=file6,status='new')
write(*,8)
8 format(' Is this case for a calorimeter with FM-26? (y or n) \'')
read(*,'(a)') answer
write(*,7)
7 format(' Enter the number corresponding to the coolant: ')
     & '          1: Water fog,/'        2: Streaming water,/'      3: AFFF,/'
     & '          4: Halon 2402 or/'      5: Liquid nitrogen')
read (*,*) iz
icount = 0
if ( icount .ne. 0 ) go to 20
read(5,*) timel, (temp1(i), i= 1,5)
10 icount = icount + 1
20 read(5,*,end=60) time2, (temp2(i), i= 1,5)
c *** calculate overall heat transfer coefficient ****
do 40 i = 1,5
dtdt = ( temp1(i) - temp2(i) ) / ( timel - time2 )
q = rhocpl * dtdt
if ( answer .eq. 'y' ) go to 30
ts = q / ( drl * ckl ) + temp2(i)
go to 40
30 tint = q / ( dr2 * ck2 ) + temp2(i)
ts = q / ( drl * ckl ) + tint
40 uoa(i) = q / ( tcool(iz) - ts )
c *** print out answers ****
write(6,45) time2, ( uoa(i) ,i= 1,5)
write(*,45) time2, ( uoa(i) ,i= 1,5)
45 format(' ',3x,f4.0,5(9x,e12.6))
c *** reset variables for next time step ****
do 50 j = 1,5
50 temp1(j) = temp2(j)
timel = time2
go to 20
60 stop
end

```

APPENDIX D
CALORIMETER TEMPERATURE/TIME PROFILES
FOR VARIOUS COOLANTS

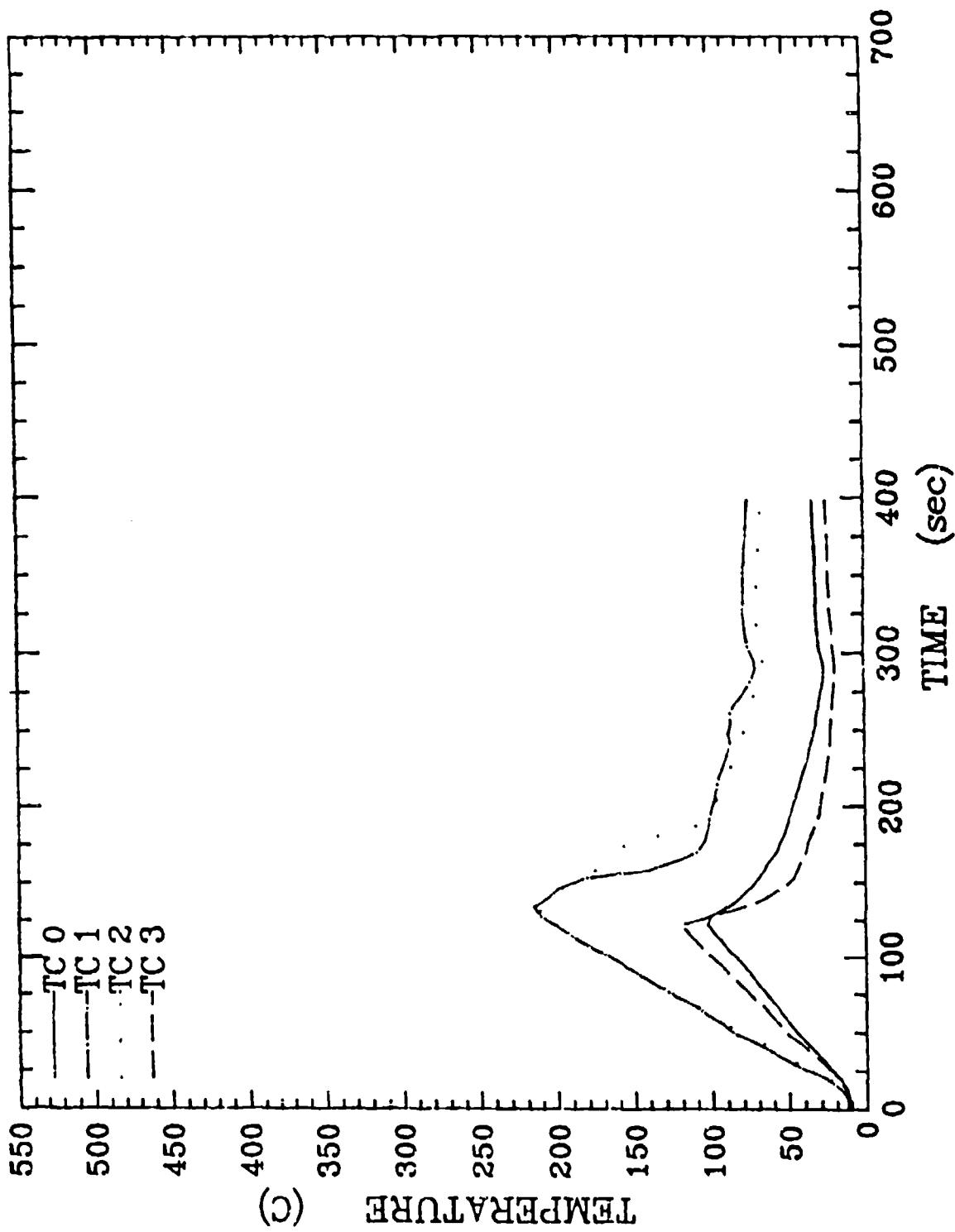


Figure D-1. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 341 L/min).

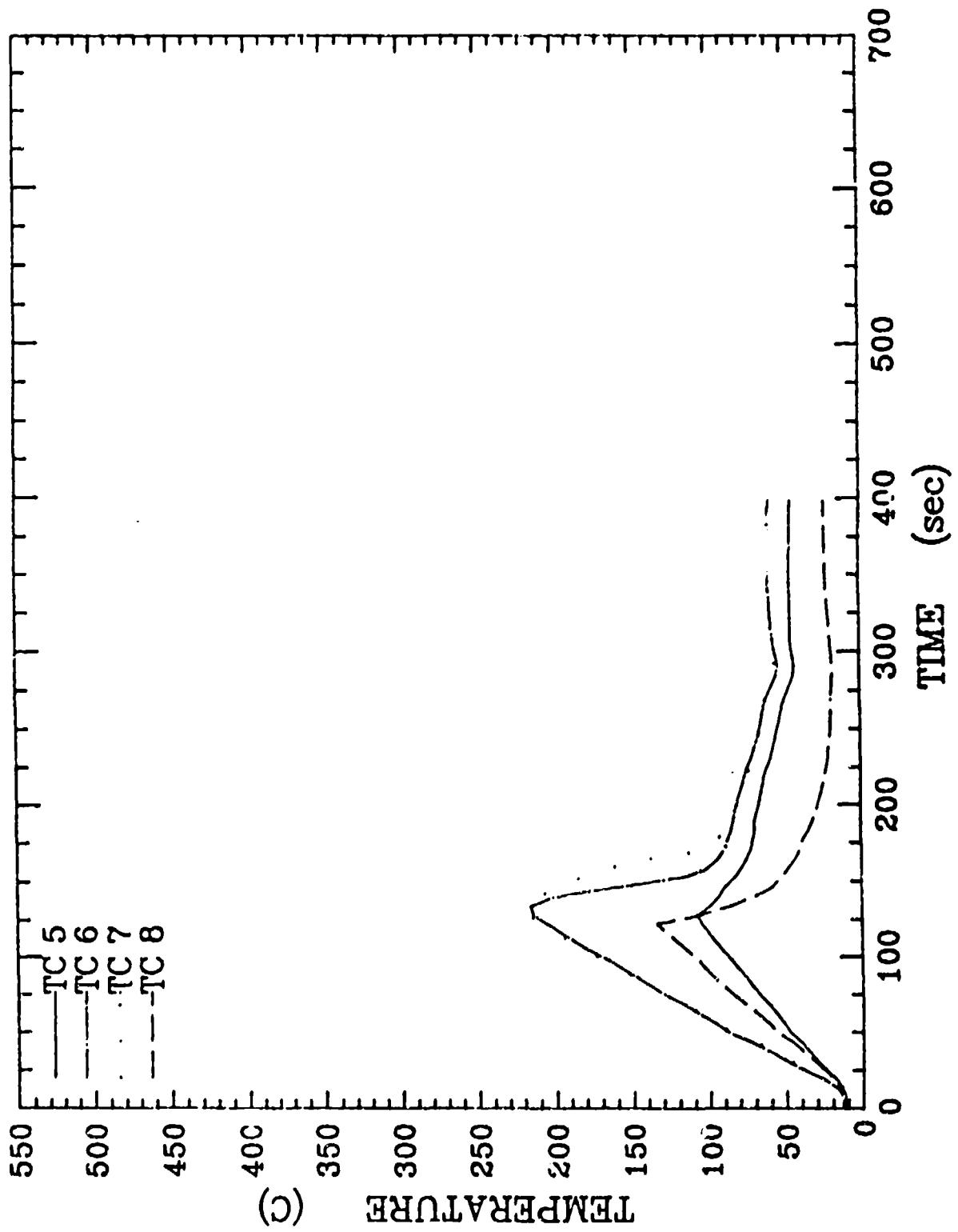


Figure D-2. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 341 L/min).

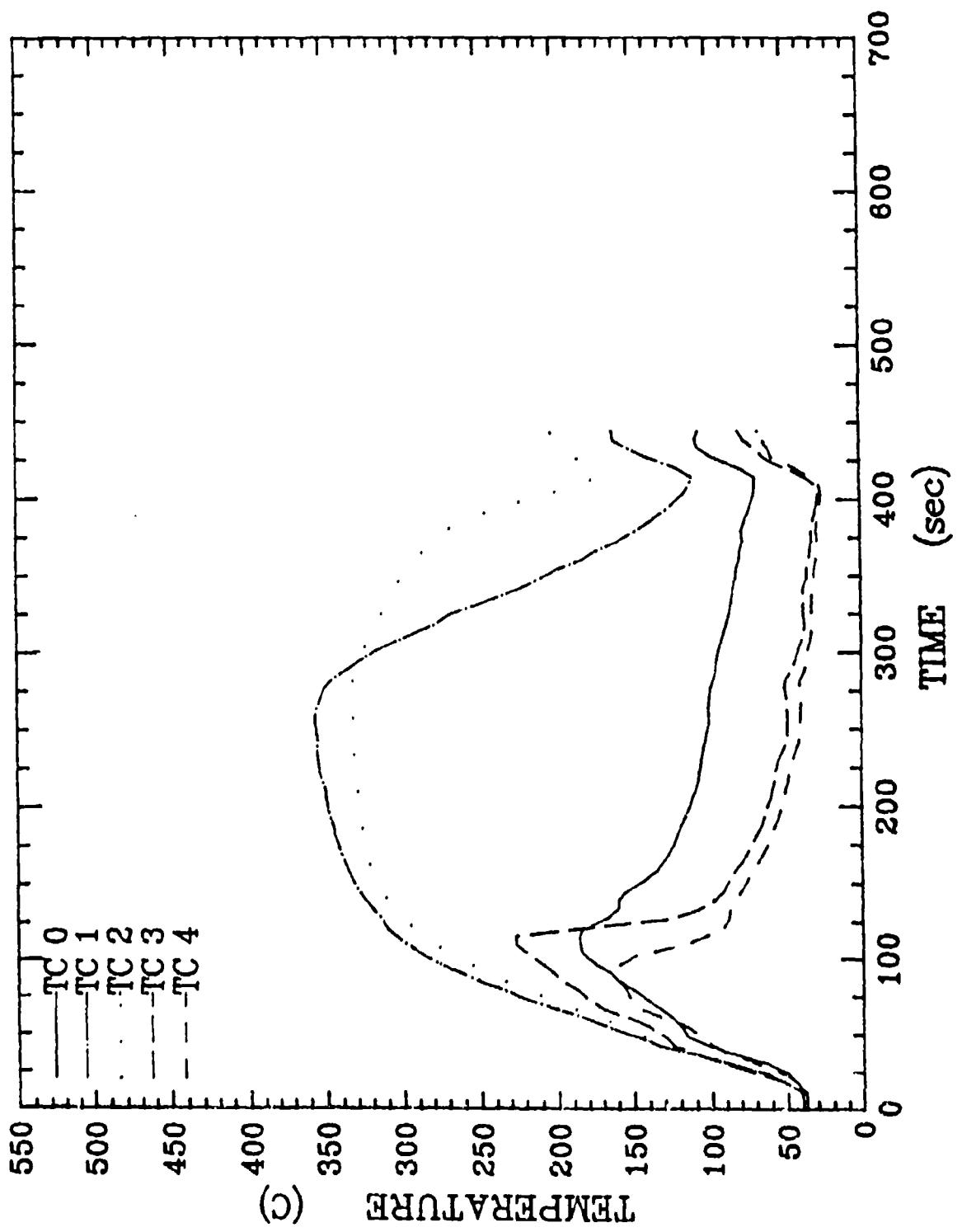


Figure D-3. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

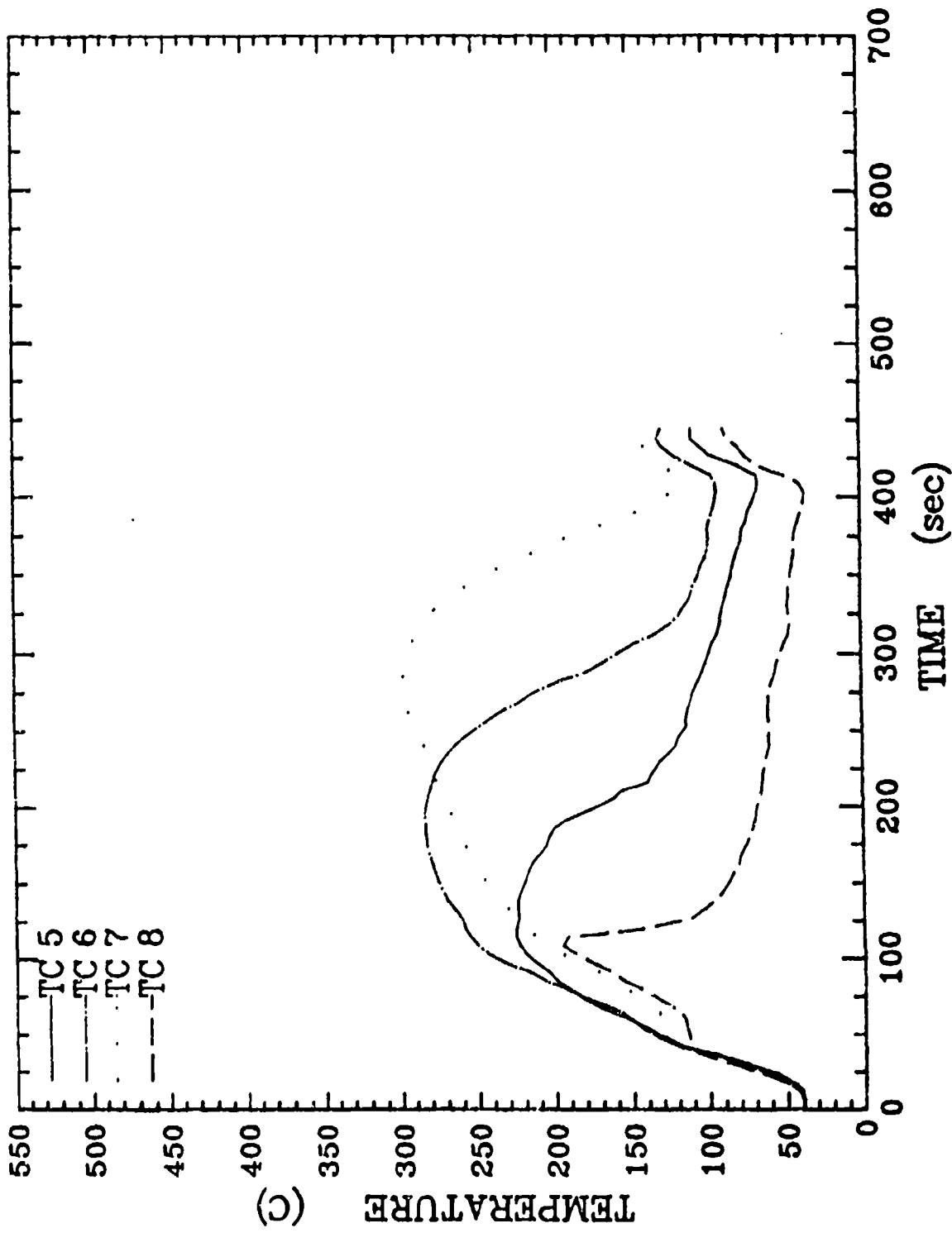


Figure D-4. Calorimeter Temperature/Time Profile (Uncoated, Water Coolant, 170 L/min).

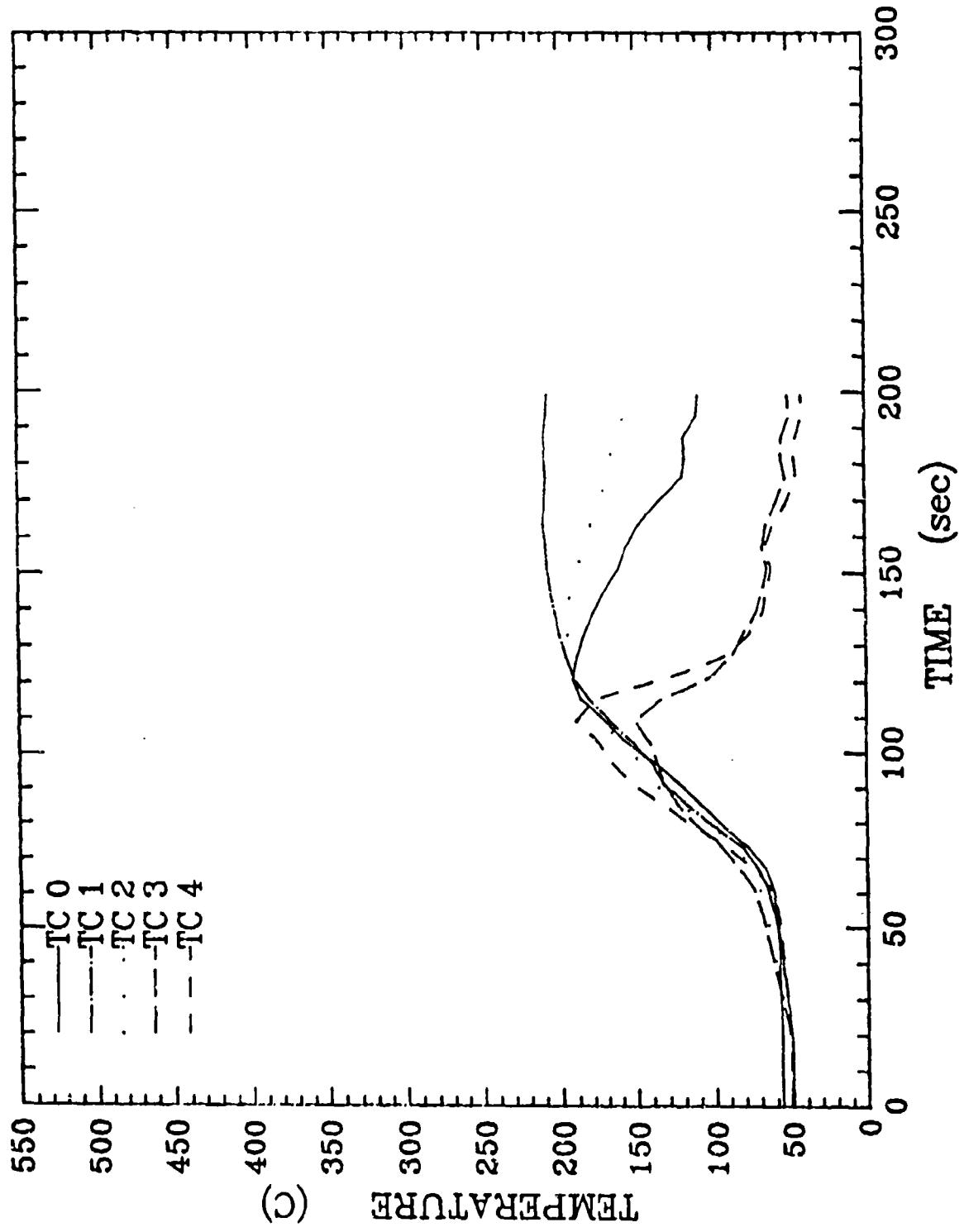


Figure D-5. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 341 L/min).

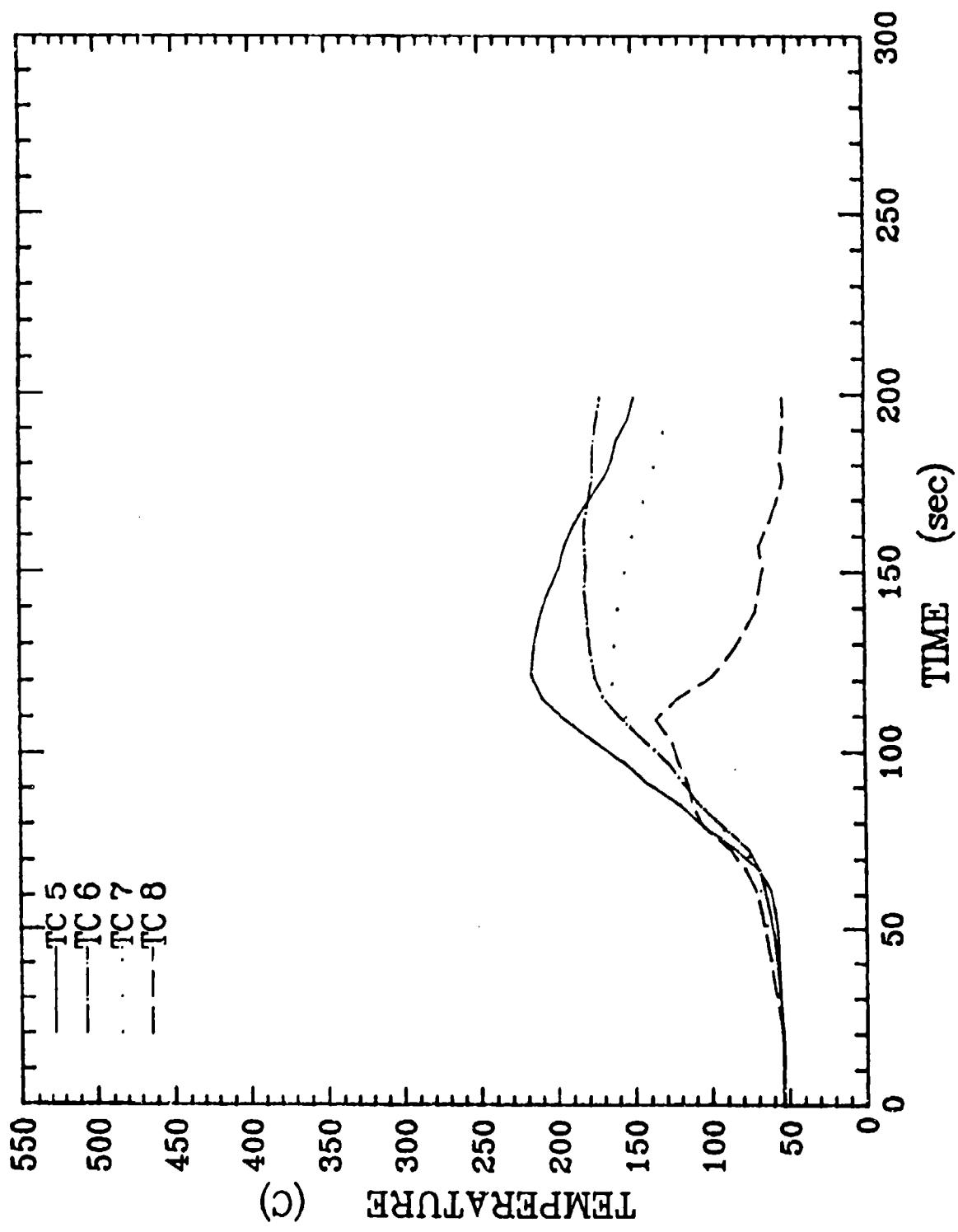


Figure D-6. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 341 L/min).

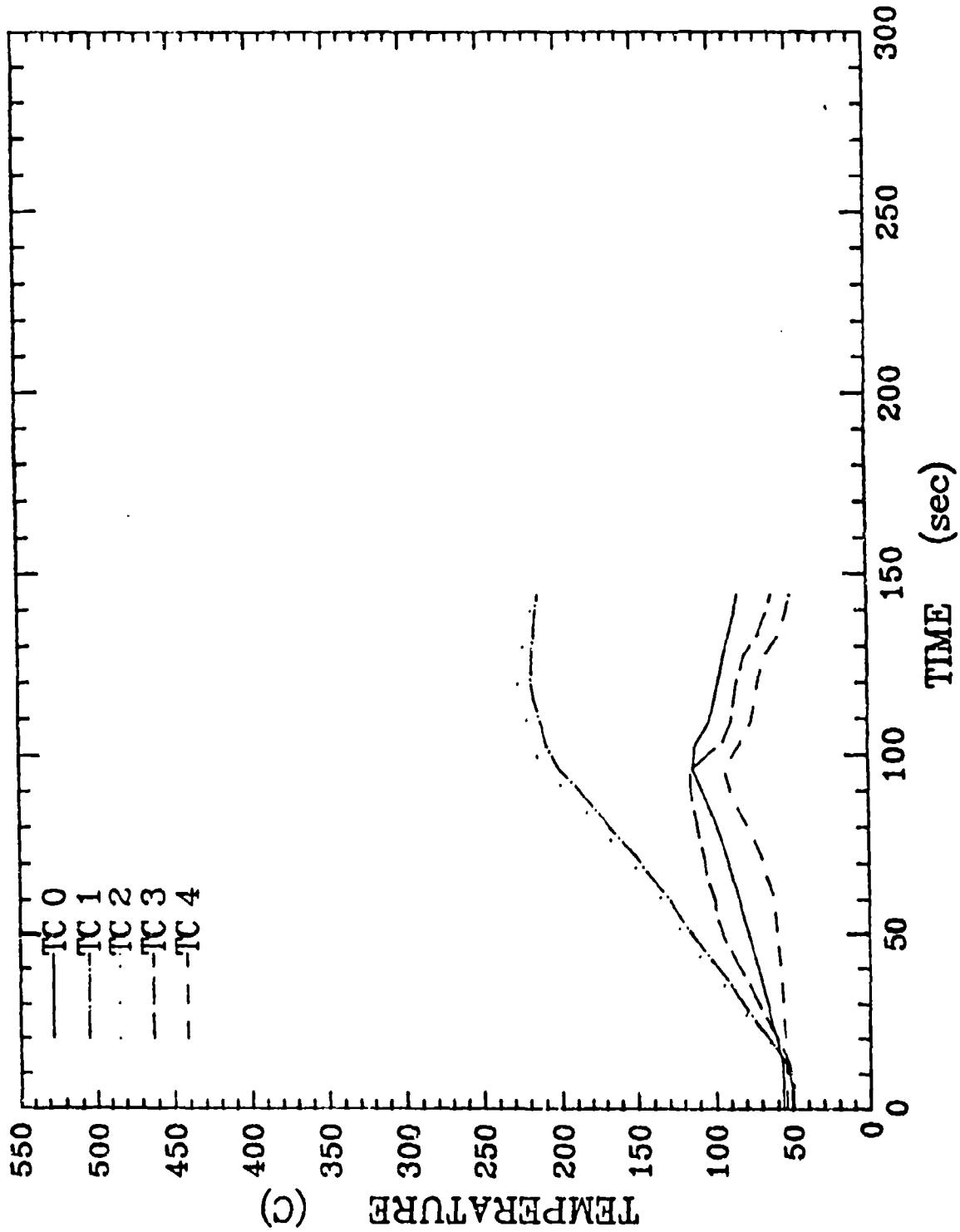


Figure D-7. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 170 L/min).

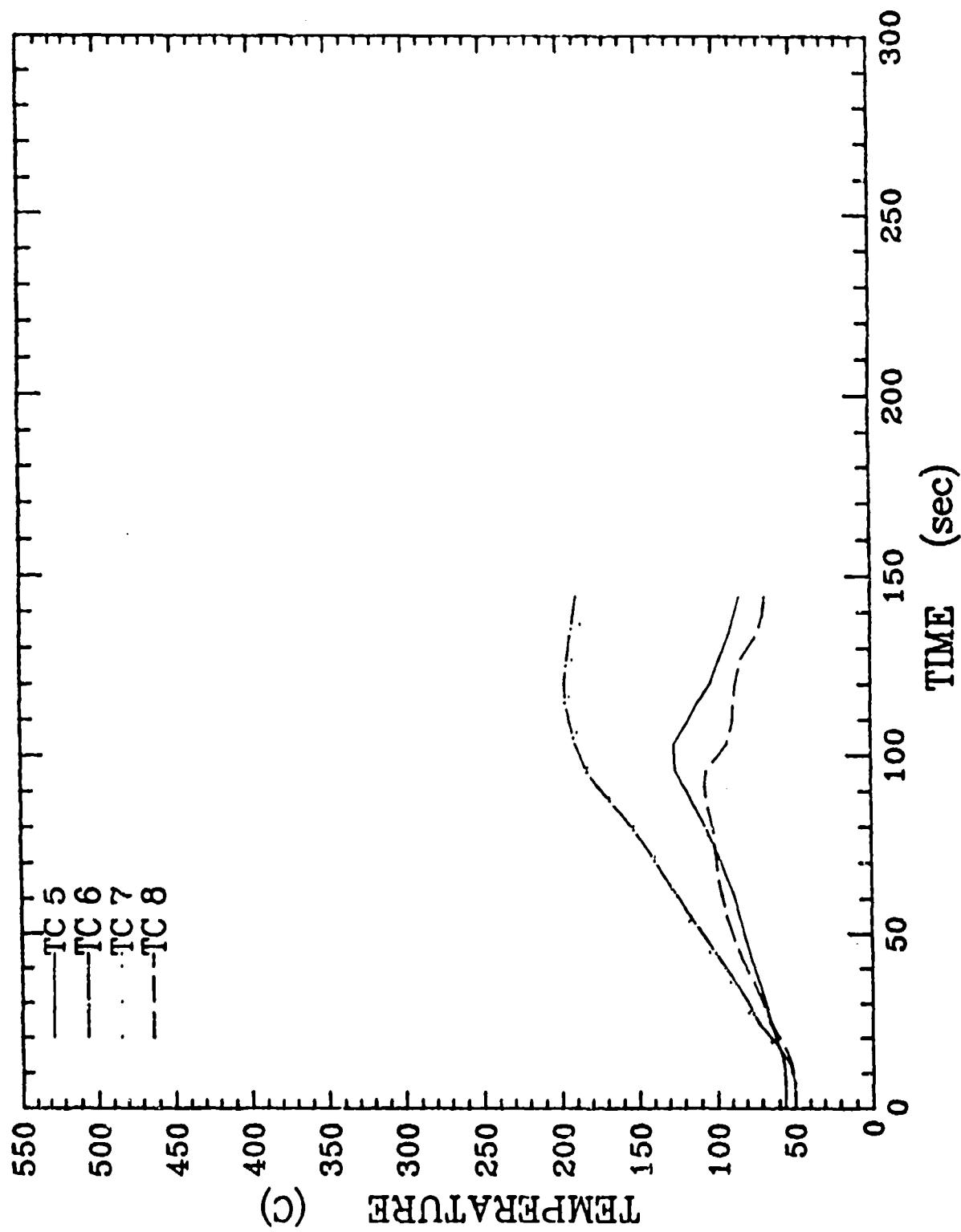


Figure D-8. Calorimeter Temperature/Time Profile (Uncoated, AFFF Coolant, 170 L/min).

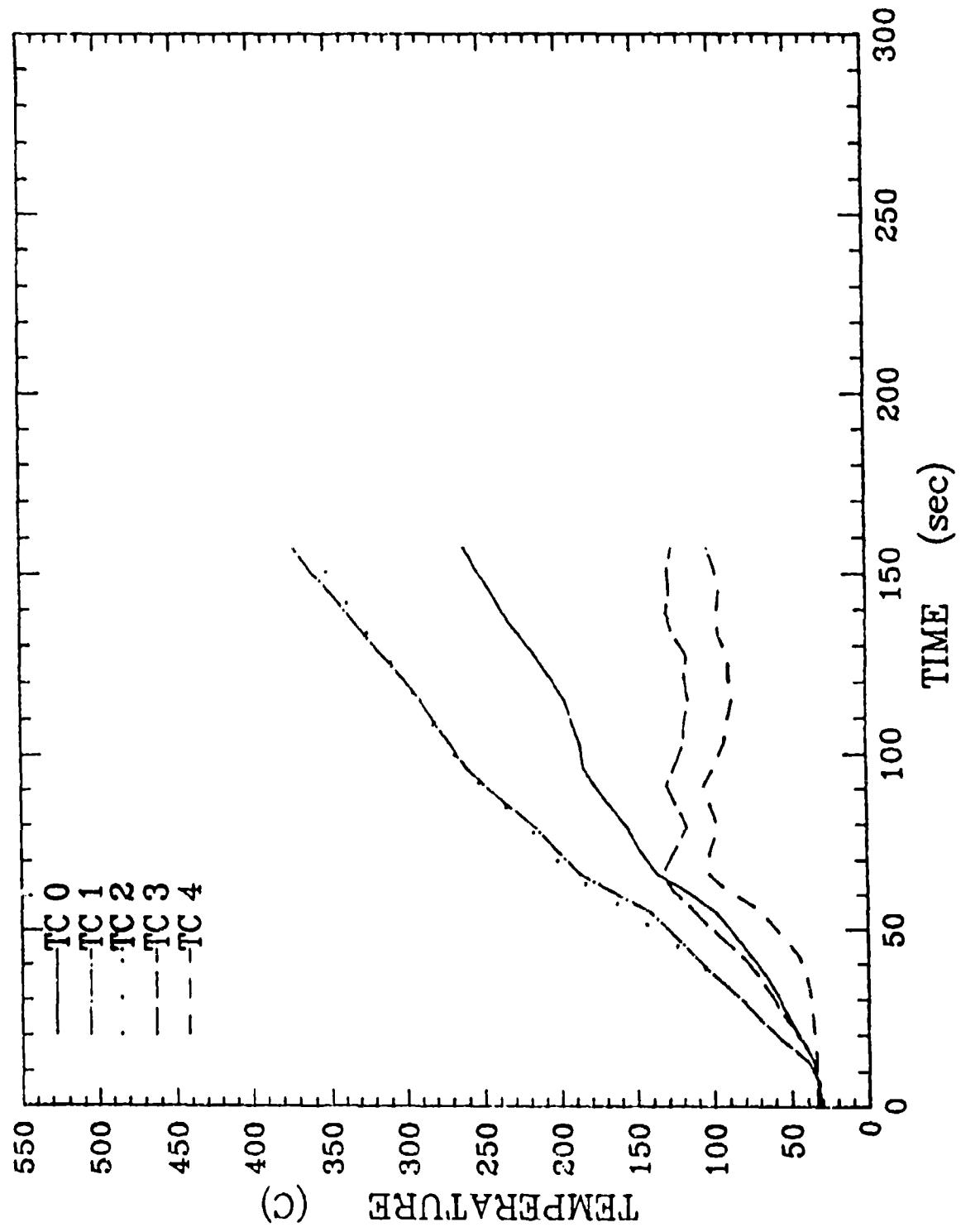


Figure D-9. Calorimeter Temperature/Time Profile (Uncoated, Halon 2402 Coolant, 2.5 kg/s).

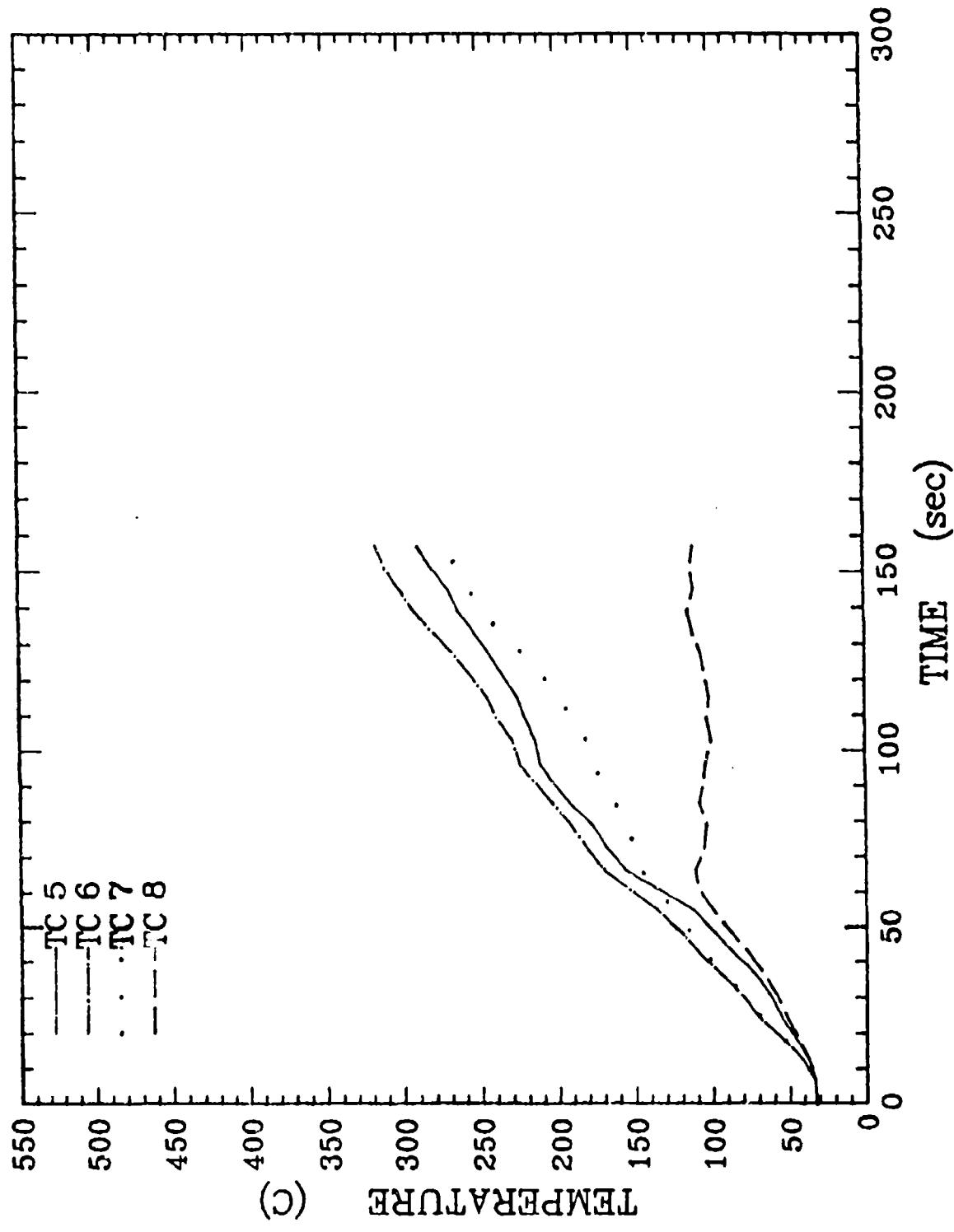


Figure D-10. Calorimeter Temperature/Time Profile (Uncoated, Halon 2402 Coolant, 2.5 kg/s).

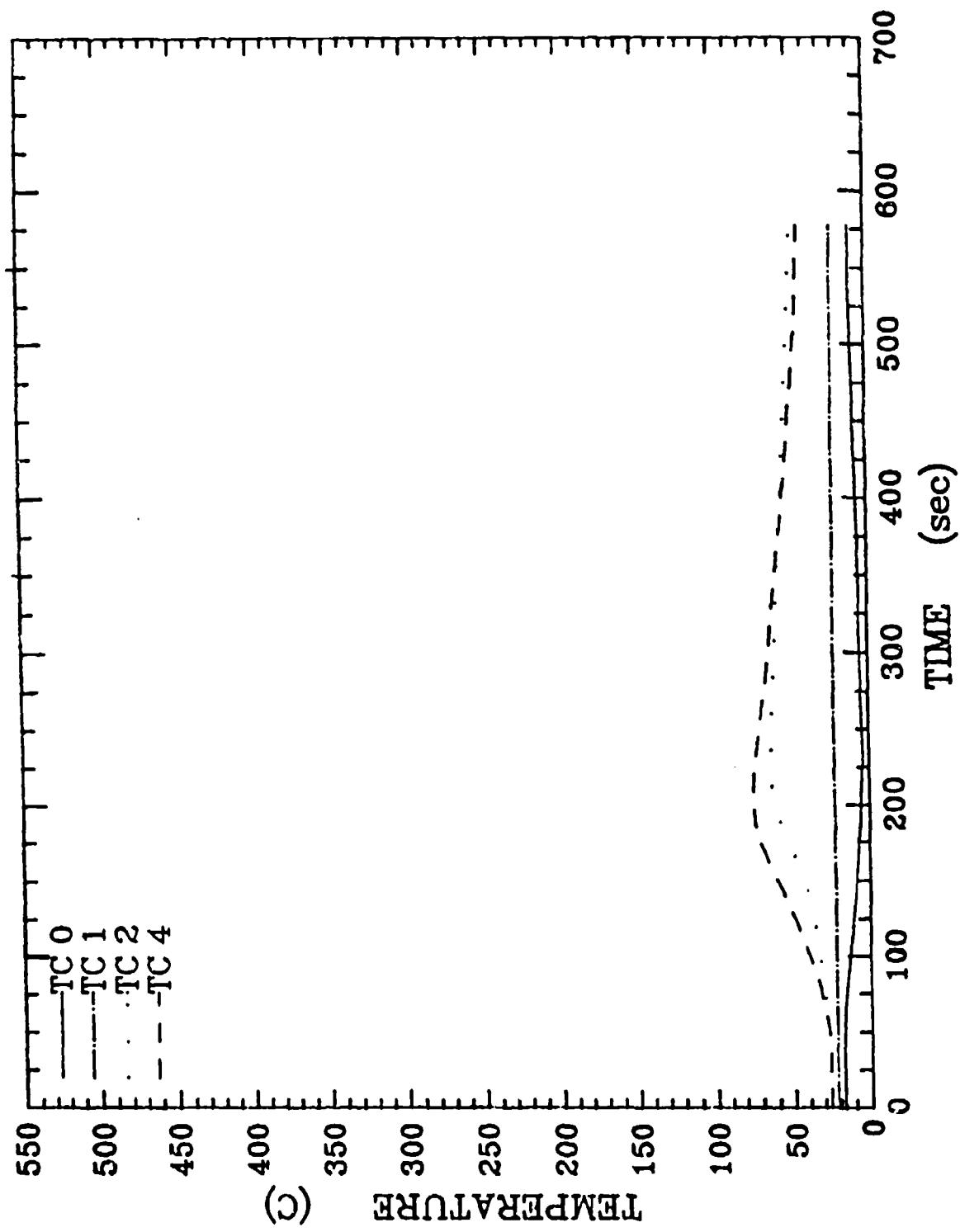


Figure D-11. Calorimeter Temperature/Time Profile (FM-26 Coating, Water Coolant, 341 L/min).

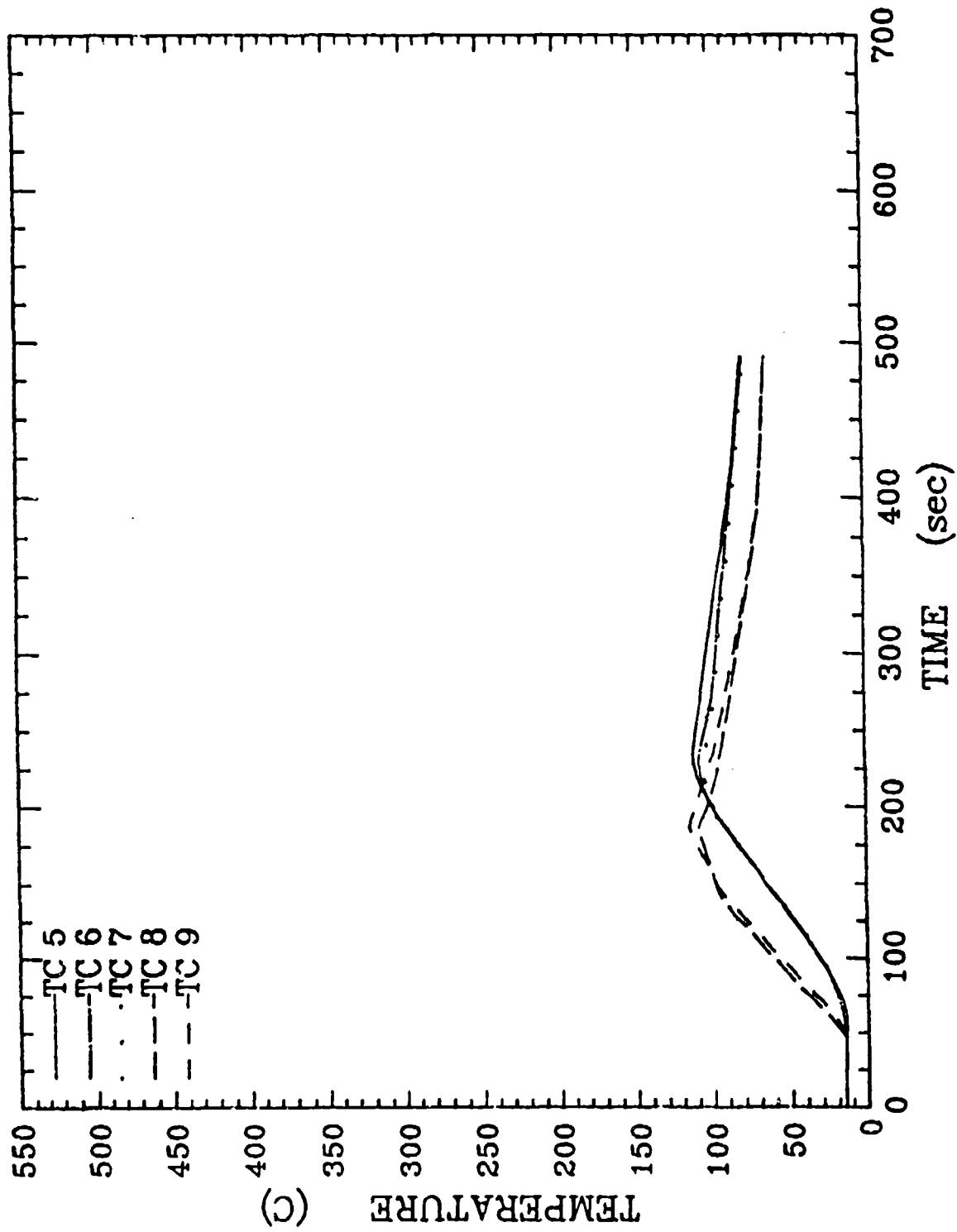


Figure D-12. Calorimeter Temperature/Time Profile (FM-26 Coating, Water Coolant, 341 L/min).

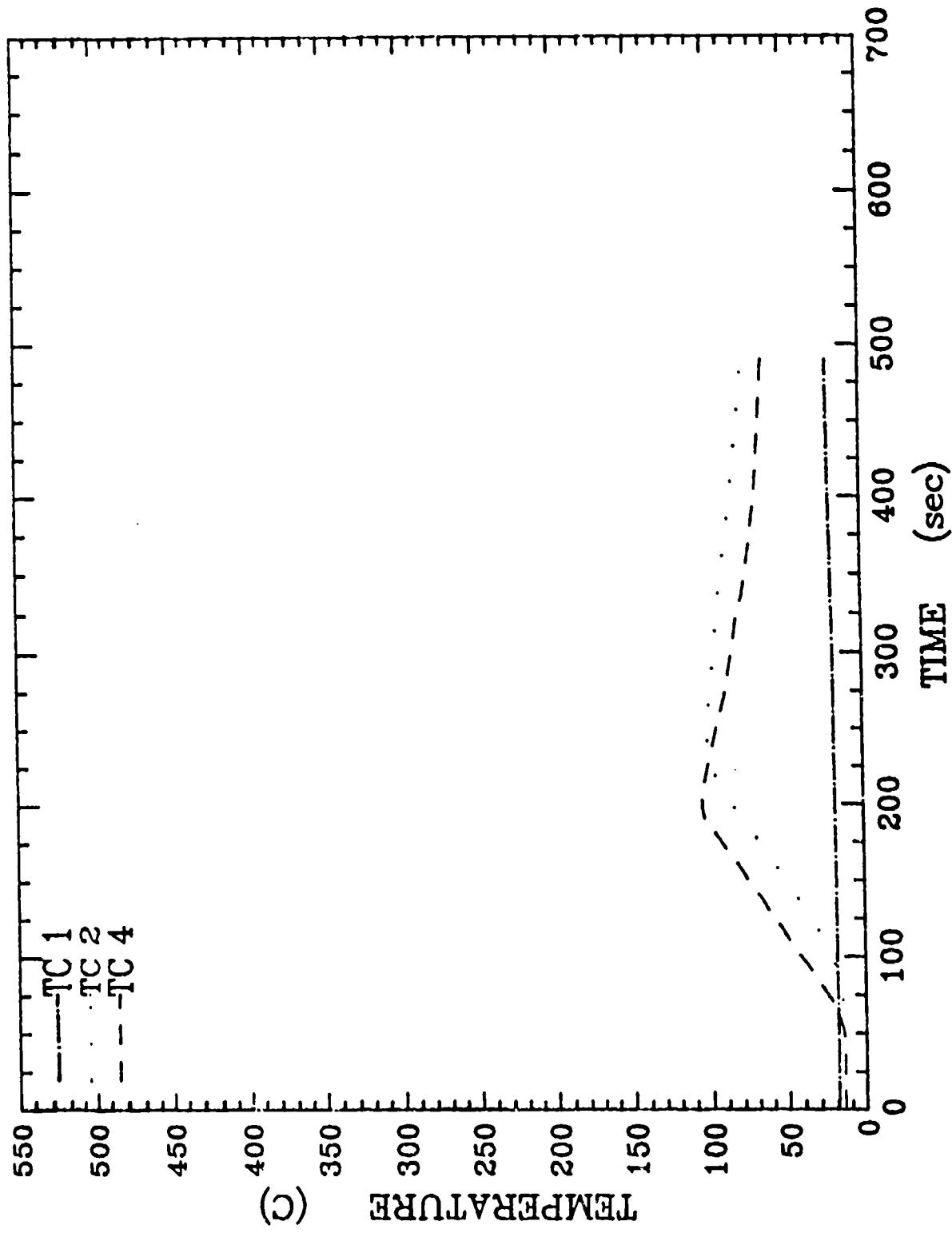


Figure D-13. Calorimeter Temperature/Time Profile (FM-26 Coating, AFFF Coolant, 341 L/min of water).

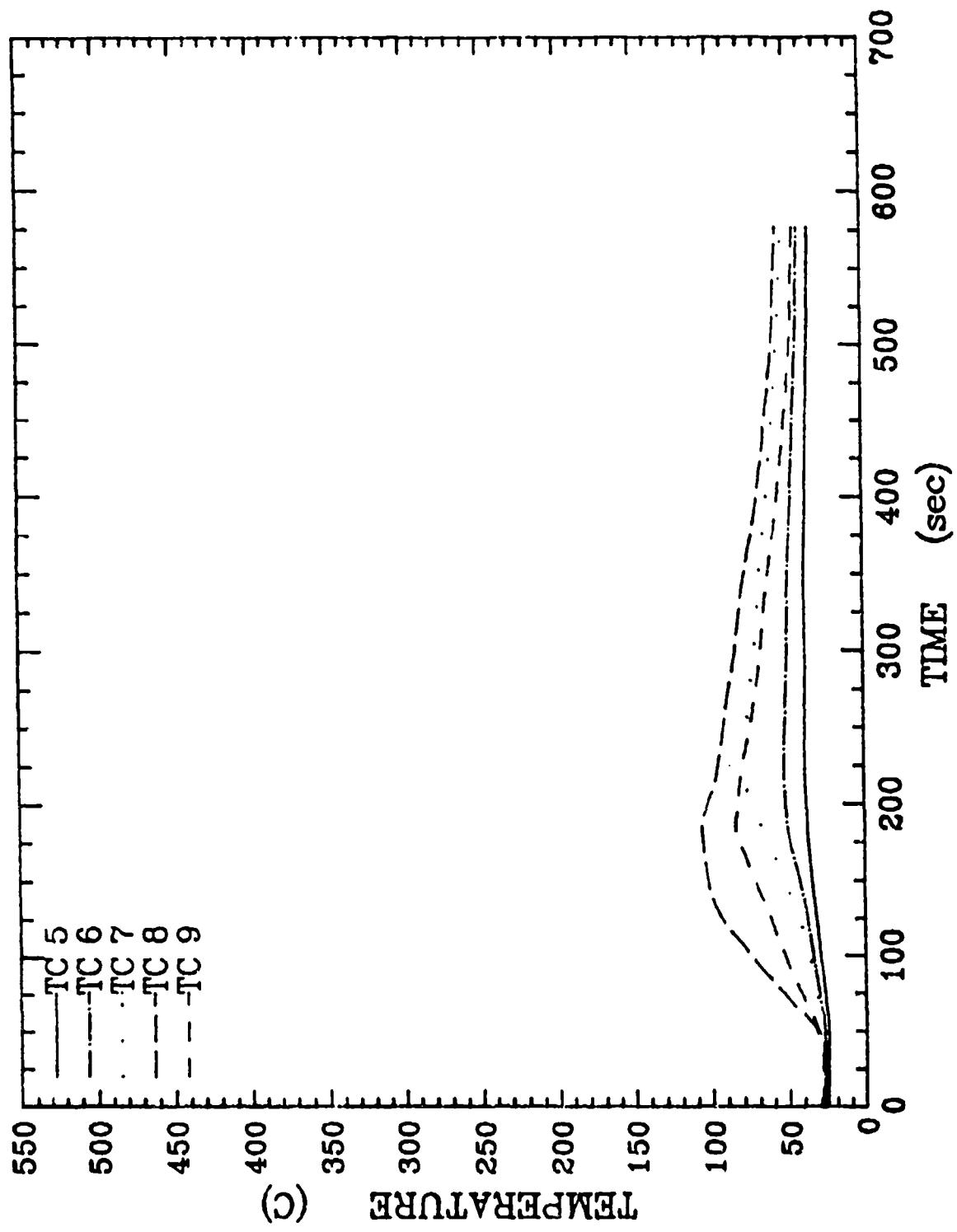


Figure D-14. Calorimeter Temperature/Time Profile (FM-26 Coating, AFFF Coolant, 341 L/min of water).

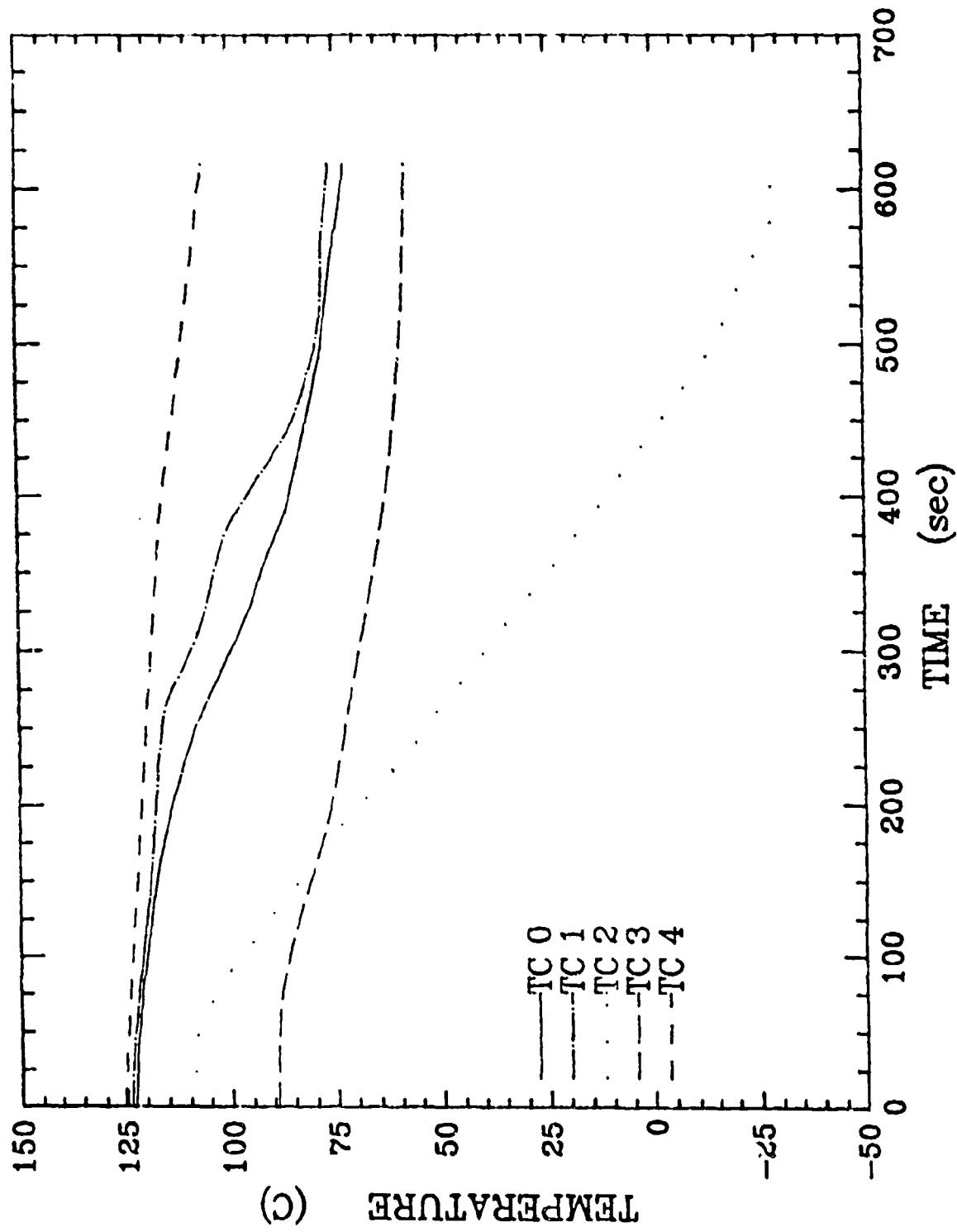


Figure D-15. Calorimeter Temperature/Time Profile (FM-26 Coating, Liquid Nitrogen Coolant).

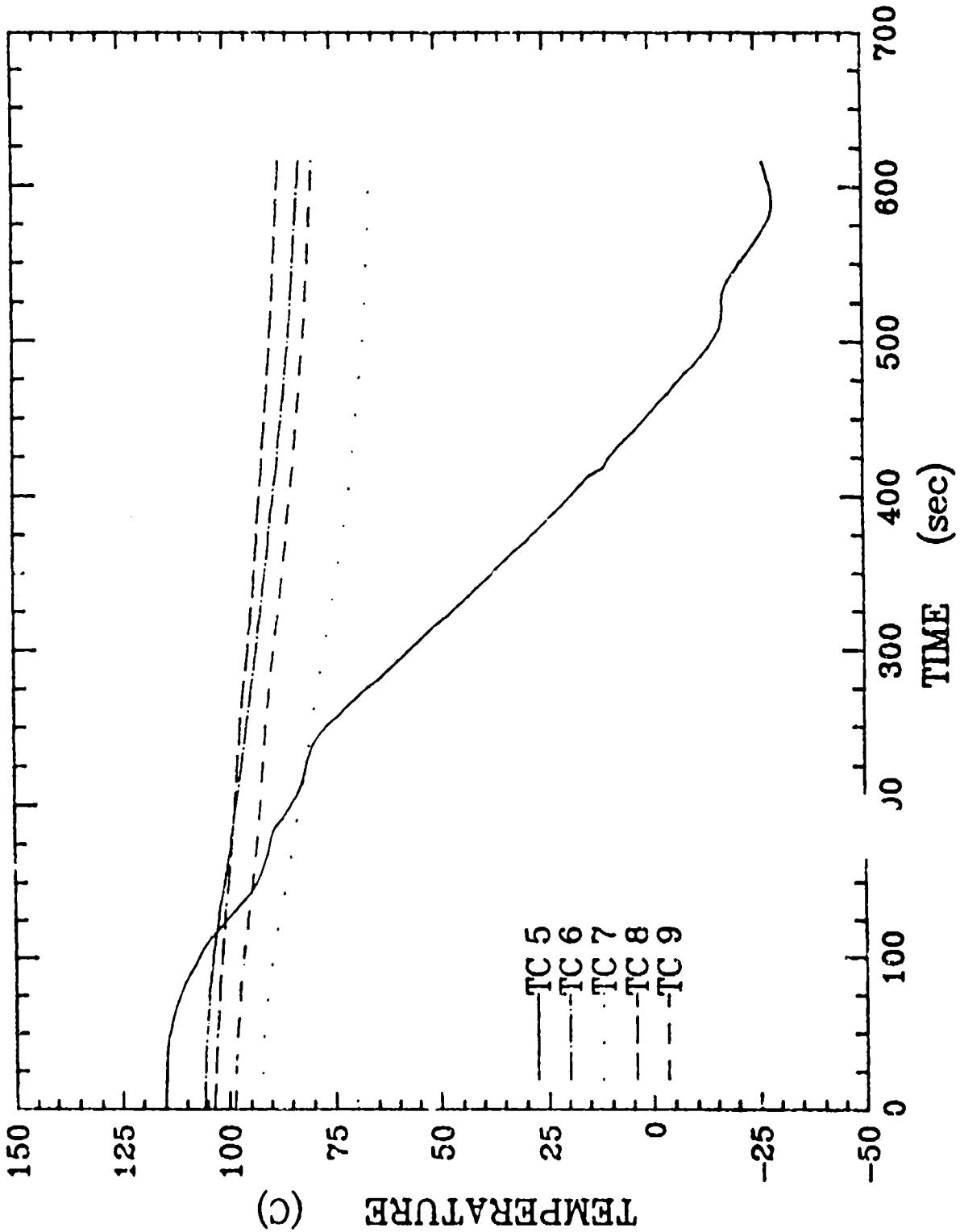


Figure D-16. Calorimeter Temperature/Time Profile (FM -26 Coating, Liquid Nitrogen Coolant).